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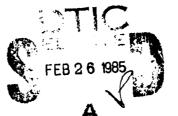
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## SECOND TOPICAL MEETING ON LASER TECHNIQUES IN THE EXTREME ULTRAVIOLET

TECHNICAL DIGEST



MARCH 5-7, 1984 BOULDER, COLORADO

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The topical meeting on lase development of sources of linear mixing, and laser prophysics; and selected novel The conference also address extreme ultraviolet. Topic high resolution and excited conversion; multiphoton exception experiments; soft x-ray last and optics.	nigh energy phot roduced plasmas; l applications s sed novel spectr cs covered inclu d state spectros	ons produced leading research as holograpic technide: laser processory; harmonicization studio	by direct let relevant aphy and x-iques application application generations; laser-s	asing actions to molecularized lithograms lithograms to the radiation so and frequesynchrotron	n, non- ar aphy. e ources; ency
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# SECOND TOPICAL MEETING ON LASER TECHNIQUES IN THE EXTREME ULTRAVIOLET

A digest of technical papers presented at the Topical Meeting on Laser Techniques in the Extreme Ultraviolet, March 5-7, 1984, Boulder, Colorado.

Cosponsored by:
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#### MONDAY, MARCH 5, 1984

8:30 AM OPENING REMARKS
S. E. Harris, Conference Cochairman

8:40 AM REMARKS Hugo Weichel, AFOSR

8:50 AM REMARKS Herschel Pilloff, ONR

XUV GENERATION AND LASERS Robert P. Madden, *Presider* 

9:00 AM MA1 (invited Paper)

Generation of Coherent Tunable VUV Radiation, R. Hilbig, G. Hilber, A. Timmermann, and R. Wallenstein, Fakultät für Physik, Universität Bielefeld, Federal Republic of Germany.

Third-order sum- and difference-frequency conversion of pulsed or cw dye-laser radiation in rare gases and metal vapors generates coherent tunable VUV radiation at wavelengths in the spectral region of  $\lambda_{vuv}=72-200$  nm.

9:30 AM MA2 (Invited Paper)

Pulsed Nozzle Techniques and Applications for the XUV, A. H. Kung, C. T. Rettner,\* E. E. Marinero,\* and R. N. Zare,† San Francisco Laser Center, Chemistry Department, University of California, Berkeley, CA.

Theory and experiments on the use of pulsed supersonic jets for third-harmonic generation and application to molecular hydrogen detection will be described.

\*IBM Research Laboratory, San Jose, CA. †Chemistry Department, Stanford University, Stanford CA.

10:00 AM MA3 (Invited Paper)

Collisionally Excited XUV Laser and XUV Radiation from Autoionizing Levels of Potassium in Discharge, Valery O. Papanyan, Institute for Physical Research, Armenian Academy of Sciences, USSR.

The talk will consider the application of quartet states of K to the construction of XUV lasers.

10:30 AM COFFEE BREAK

#### **MONDAY, MARCH 5, Continued**

11:00 AM MA4 (Invited Paper)

Soft X-Ray Laser Experiments at the Novette Laser Facility, D. Matthews, P. Hagelstein, R. Kauffman, R. Lee, C. Wang, H. Medecki, M. Campbell, N. Ceglio, G. Stone, G. Leipelt, P. Lee, P. Drake, L. Pleasance, L. Seppala, W. Hatcher, G. Rambach, G. Heaton, R. Price, R. Ozarski, R. Speck, K. Manes, J. Underwood, A. Toor, T. Weaver, L. Coleman, B. DeMartini, J. Auerbach, R. Turner, W. Zagotta, A. Hawryluk, and M. Rosen, Lawrence Livermore National Laboratory, Livermore, CA.

We discuss the results of and future plans for experiments to study the possibility of producing an x-ray laser at the Novette Laser Facility. The schemes we have investigated are all pumped by the Novette Laser operated at short pulse ( $\tau_L \sim 100$  psec) and an incident wavelength of ( $\lambda_L \sim 0.52\,\mu\text{m}$ ). We have investigated the possibility of lasing at 53.6, 68.0 – 72.0, 119.0, and 153.0 eV using the methods of resonant photoexcitation, collisional excitation, and three-body recombination.

11:30 AM MA5 (Invited Paper)

Tunable Sub-Angstrom Radiation Generated by Anti-Stokes Scattering from Nuclear Levels, C. B. Collins and B. D. DePaola, Center for Quantum Electronics, University of Texas at Dallas, Richardson, TX.

Experiments show that radiation tunable over tens of linewidths near 0.1 nm can be produced by anti-Stokes scattering from excited nuclear levels of <sup>87</sup>Fe.

12:00 N MA6 (Invited Paper)

Zone Plates and Their Applications in Soft X-ray Imaging, Janos Kirz, Department of Physics, State University of New York, Stony Brook, NY.

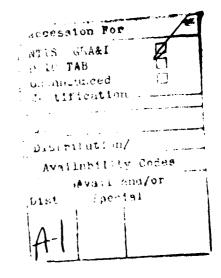
Zone plates have emerged as important optical elements in the XUV. Their properties, fabrication, and applications will be discussed, with emphasis on X-ray microscopy using synchrotron radiation.

12:30 PM MA7

Recent Experiments on Soft X-Ray Laser Development in a Confined Plasma Column, S. Suckewer, C. Keane, H. Milchberg, C. H. Skinner, and D. Voorhees, Plasma Physics Laboratory, Princeton University, Princeton, NJ.

We present studies of magnetically confined and expanding recombining plasma columns and gain measurements for hydrogen-like (C vi) and Li-like (C iv, O vi, F vii, and Ne viii) ions.

12:45 PM-2:00 PM LUNCH





#### **MONDAY, MARCH 5, Continued**

#### **AUTO-IONIZING AND MULTIPHOTON PROCESSES** Steve Smith. *Presider*

#### 2:00 PM MB1 (Invited Paper)

Anomalous Multiphoton Processes, C. K. Rhodes, Department of Physics, University of Illinois at Chicago, Chicago, Ill.

The interaction of 193-nm radiation with atoms at intensity levels up to ~ 10<sup>16</sup> W/cm² is studied. Anomalous collision-free ionization and XUV radiation are observed.

#### 2:30 PM MB2 (Invited Paper)

Multiply Charged Ions Produced by Multiphoton Absorption, A. L'Huillier, L. A. Lompre, G. Mainfray, and C. Manus, Centre d'Etudes Nucléaires de Saclay, Service de Physique des Atomes et des Surfaces, France.

Multiply charged ions are produced by multiphoton ionization of rare-gas atoms with 50-psec laser pulses at 532 and 1064 nm in the 1012-1015 W/cm<sup>-2</sup> range.

#### 3:00 PM MB3 (invited Paper)

Laser Enhanced Auto-ionization and Dressed Resonances, J. H. Eberly and D. Agassi, Department of Physics and Astronomy, University of Rochester, Rochester, NY.

We describe the strong field dressing of atomic resonance states and apply the dressed state description to photoexcitation of an auto-ionizing resonance, including the effects of radiative and purely transverse line broadenings.

#### 3:30 PM MB4 (Invited Paper)

Planetary Atoms, William E. Cooke, Richard R. Freeman,\* Robert M. Jopson,\* and J. Bokor,†, Physics Department, University of Southern California, Los Angeles, CA.

We have used four-photon excitation to populate msns,  $^{1}S_{0}$  planetary states of barium with m values of 7 through 11 and n values of 12 and larger.

\*Bell Telephone Laboratories, Murray Hill, NJ. †Bell Telephone Laboratories, Holmdel, NJ.

#### 4:00 PM COFFEE BREAK

#### **MONDAY, MARCH 5, Continued**

#### 4:30 PM MB5 (Invited Paper)

Multiphoton ionization of Alkali Atoms, R. N. Compton, A. Dodhy, J. A. D. Stockdale, and Cornelius E. Klots, Chemical Physics Section, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN.

We discuss recent experiments on single- and multiple-photon ionization of alkali atoms both in the presence and absence of an external electric field.

#### 5:00 PM MB6 (Invited Paper)

Photoionization of Excited Molecular States Using Multiphoton Excitation Techniques, P. M. Dehmer, S. T. Pratt, and J. L. Dehmer, Argonne National Laboratory, Argonne, IL.

Electronic and vibrational branching ratios following photoionization of Rydberg states of  $H_z$  and  $N_z$  were determined using photoelectron spectroscopy to probe the final ionic states.

#### 5:30 PM MB 7

State-to-State Photochemistry of Glyoxal Using a Tunable VUV Laser for Product Detection, John W. Hepburn, N. Sivakumar,\* and Paul L. Houston,\* Centre for Molecular Beams and Laser Chemistry, Department of Chemistry, University of Waterloo, Waterloo, Ontario, Canada.

The predissociation of glyoxal has been studied by laser excitation of glyoxal molecules in a supersonic beam, followed by VUV laser-induced fluorescence detection of the photo-fragments.

\*Department of Chemistry, Cornell University, Ithaca, NY.

#### 5:45 PM MB8

Multiphoton ionization of Benzene in Solution, K. Slomos, H. Faidas, and L. G. Christophorou, Atomic, Molecular and High Voltage Physics Group, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN.

The  $B_{2u}$ - $A_{1g}$  transitions of benzene in solution have been observed for the first time in a two-photon resonant three-photon ionization experiment. The linearly polarized spectrum is reported, and the benzene's ionization threshold is discussed.

#### **MONDAY, MARCH 5, Continued**

#### 7:00-9:00 PM POSTER SESSION

#### MULTIPHOTON IONIZATION

#### MC1 (Withdrawn Paper)

#### (Poster Paper) MC2

Multiphoton ionization of Cesium Atoms above and below the Two-Photon ionization Threshold, A. Dodhy, J. A. D. Stockdale, and R. N. Compton, Chemical Physics Section, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN.

Photoelectron angular distributions are reported for multiphoton ionization of cesium for photon energies below and above the two-photon ionization threshold.

#### MC3 (Poster Paper)

Two- and Three-Photon Ionization of Cesium, Michael S. Pindzola, Department of Physics, Auburn University, Auburn,

Probabilities for the two- and three-photon ionization of cesium are calculated using the density-matrix formalism.

#### MC4 (Poster Paper)

Multiphoton Ionization Spectroscopy of the Fluoromethyl Radical, C. S. Dulcey, Denis J. Bogan, and Jeffrey W. Hudgens, Chemistry Division, Naval Research Laboratory, Washington,

The electronic spectrum of the CH<sub>2</sub>F radical has been observed for the first time via mass-resolved, two-photon resonanceenhanced multiphoton ionization spectroscopy.

#### MC5 (Poster Paper)

Grotrian Diagram of Core-Excited Quartets in Na I, D. E. Holmgren, D. J. Walker, D. A. King, and S. E. Harris, Edward L. Ginzton Laboratory, Stanford University, Stanford, CA.

Twenty-eight Na emission lines are identified as transitions between core-excited quartet states of Na I. The classifications are confirmed by Hartree-Fock calculations and observed laser-enhanced fluorescence.

#### INSTRUMENTATION

#### MD1 (Poster Paper)

Variable Line Space Slitless Spectrometers at Grazing Incidence, M. C. Hettrick, University of California, Berkeley, Space Sciences Laboratory, Berkeley, CA.

Spectrometer configurations composed of variable-line-space in-plane, conical and echelle combination plano gratings are analyzed through ray tracing and efficiency calculations. Trade-offs are discussed.

#### **MONDAY, MARCH 5, Continued**

#### MD2 (Poster Paper)

VUV Instrument Calibrations for Laser-Plasma Studies, Paul D. Rockett, C. Richard Bird, and Ronnie Shepherd, KMS Fusion, Inc., Ann Arbor, MI.

Techniques for spectral and intensity calibrations of laserplasma VUV instrumentation will be described. A flexible laboratory x-ray station is shown to yield creditable results.

#### MD3 (Poster Paper)

High-Resolution VUV Spectrometer with Electronic Parallel Spectral Detector, C. L. Cromer, J. M. Bridges, T. B. Lucatorto. and J. R. Roberts, National Bureau of Standards, Washington,

A new VUV spectrometer designed for photoabsorption studies will be described. This instrument features an enhanced-resolution, VUV-optical multichannel analyzer and a laser-plasma continuum source.

#### MD4 (Poster Paper)

Photoemissive Materials for 0.35  $\mu m$  Laser Fiducials in X-Ray Streak Cameras, Charley P. Hale, Hector Medicki, and Peter H. Y. Lee, Lawrence Livermore National Laboratory, University of California, Livermore, CA.

Using a soft x-ray streak camera, materials are tested for suitability as transmission photocathodes when irradiated by 0.35-µm laser pulses. Preliminary measurements of sensitivity, dynamic range, and temporal resolution are reported. A practical fiber-optic fiducial under development for laser fusion x-ray diagnostics on the LLNL Nova laser system is described.

MD5 (Poster Paper) XUV Gain Amplification Studies in Laser Plasma Using Normal-Incidence Multilayer Mirrors, P. Dhez,\* G. Jameiot, A. Carillon, and P. Jaegle, C.N.R.S., Université Paris-Sud, Orsay, France.

The present state of art in multilaver mirrors and in XUV population inversion production in a laser plasma allows us to test a possible laser cavity.

\*LURE, Orsay, France.

#### MD6 (Poster Paper)

Performance of Transition Metal-Carbon Multilayer Mirrors from 80 to 350 eV, D. R. Kania, R. J. Bartlett, W. J. Trela, E. Spiller,\* and L. Golub,† Physics Division, Los Alamos National Laboratory, Los Alamos, NM.

We report measurements and theoretical calculations of the reflectivity and resolving power in first and second order of multilayer mirrors made of alternate layers of a transition metal (Co, Fe, V, and Cr) and carbon (2d = 150 Å) from 80 to 350 eV.

\*T. J. Watson Research Center, IBM Corporation, Yorktown Heights, NY.

† Harvard Smithsonian Center for Astrosphysics, Cambridge, MA.

#### TUESDAY, MARCH 6, 1964

(UV SPECTROSCOPY lames J. Wynne, Presider

k00 AM TuA1 (Invited Paper)

Molecular Dynamics Probed by VUV Radiation, John C.

Polanyi, University of Toronto, Toronto, Canada.

Laser-induced fluorescence has proved to be a powerful tool for the study of inelastic collisions in gases and at surfaces. Joys and sorrows experienced in the attempt to extend such measurements into the VUV will be discussed and exemplified.

9:30 AM TuA2 (Invited Paper)

VUV Spectroscopy of Hydrogen, K. H. Welge, Universität Bielefeld, West Germany.

Two-photon Stark spectroscopy has been carried out with the H atom by resonant excitation through selected Stark components in n=2 at Lyman  $\alpha$  from the classical field ionization saddle point energy up to and beyond the zero-field ionization limit around 1100 Å. Two-photon spectroscopy of the  $H_2$  molecule with photoionization and dissociation from selected B(v'=0,J') has been investigated with a tunable vuv laser around 1100 Å.

10:00 AM TuA3 (Invited Paper)
Use of Synchrotron and Laser Radiation for Present and
Future ionization Studies in Excited Atoms and in Ions, F.
Wuilleumier, LURE, University of Paris Sud, Orsay, France.

This paper reviews the present status of laser-synchrotron ionization experiments in excited atoms and the opportunities opened up by future sources of synchrotron radiation.

#### 10:30 AM COFFEE BREAK

11:00 AM TuA4 (Invited Paper)
State-Selective VUV Spectroscopy of Small Molecules, C. R. Vidal, Max-Planck-Institut für extraterrestrische Physik, Federal Republic of Germany.

State-selective spectroscopy of the CO and NO molecule is demonstrated using the methods of fluorescence, of frequency-selective excitation, and of vuv-visible double-resonance spectroscopy.

#### 11:30 AM TuA5

\*\*Kr Detection Using Resonance Ionization Spectroscopy, C. H. Chen, S. D. Kramer, S. L. Allman, and G. S. Hurst, Oak Ridge National Laboratory, Oak Ridge, TN.

A vuv laser was produced by a four-wave mixing scheme to excite krypton. Resonance ionization spectroscopy and a mass spectrometer were used to count 1000 atoms of \*1Kr.

#### TUESDAY, MARCH 6, Continued

#### 11:45 AM TuA6

Spectroscopic Study of Xe Dimer Using VUV Laser Excitation, R. H. Lipson, P. E. LaRocque, and B. P. Stoicheff, Department of Physics, University of Toronto, Toronto, Ontario, Canada.

New fluorescence-excitation spectra of  $Xe_2$  (produced in a pulsed supersonic jet) have been obtained at high resolution at 130 and 149 nm using tunable coherent VUV radiation generated by 4-WSM in Mg and in Zn.

#### 12:00 N TuA7

VUV Photolonization of Cold Molecular Beams: Single and Multiphoton ionization and Photoelectron Spectroscopy, John C. Miller and R. N. Compton, Chemical Physics Section, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN.

Experiments combining nonlinear optics, mass- and energyresolved ion detection, and a supersonic nozzle to study vuv photoionization and photoelectron spectroscopy of ultracold molecules will be described.

#### **TUESDAY, MARCH 6, Continued**

#### **IERATION WITH ELECTRON BEAMS** incaid. Presider

PM TuB1 (Invited Paper)

erent Radiation Characteristics of Magnetic Insertion ices in Modern Storage Rings, K. O. Kim, K. Halbach, and Attwood, Center for X-Ray Optics, Lawrence Berkeley pratory, University of California, Berkeley, CA.

discuss the characteristics of radiation from undulators wigglers in modern electron storage rings. Of particular inst are the coherence properties of undulator radiation that ides an assured route to tuneable coherent radiation ughout the soft x-ray spectral region. We discuss spectral, ular, spatial, and polarization properties of this radiation.

PM TuB2 (invited Paper) eration of Coherent XUV Radiation Using Lasers and itivistic Electron Beams, R. R. Freeman and B. M. Kincaid, T Bell Laboratories, Murray Hill, NJ.

erent soft x rays can be produced by bunching a tivistic electron beam with a high-powered visible laser.

#### PM TuB3

/VUV Free-Electron Laser Oscillator, John C. Goldstein, n E. Newnam, Richard K. Cooper, and John S. Fraser, Los nos National Laboratory, Los Alamos, NM.

ree-electron laser oscillator driven by an rf linear acrator appears feasible for the XUV and VUV wavelength ctrum from 50 to 200 nm.

#### PM TuB4

eme Ultraviolet and X-Ray Emission and Amplification by relativistic Electron Beams Traversing a Superlattice, A. E. lan and S. Datta, School of Electrical Engineering, Purdue versity, West Lafayette, IN.

demonstrate the feasibility for obtaining extreme UV and x-ray radiation using nonrelativistic electron beams ersing a solid-state superlattice with a short spatial period.

#### COFFEE BREAK

#### **TUESDAY, MARCH 6, Continued**

**MIRRORS, OPTICS, AND MICROSCOPY** N. M. Ceglio, Presider

4:00 PM TuC1 (Invited Paper)

Multilayer Optics for the XUV: Synthesis, Experimental Results, and Projected Performance, Troy W. Barbee, Jr., Materials Sciences Engineering, Stanford University, Stanford,

Advanced vapor deposition techniques have yielded a new class of multi-layer optics for soft X-rays. Applications of these processes to fabrication of XUV optics promises significant improvements. Synthesis processes, current experimental results, and projected performance are discussed.

4:30 PM TuC2 (invited Paper)

Mirrors for the Extreme Ultraviolet, Eberhard Spiller, IBM Research Center, Yorktown Heights, NY.

The status of multilayer mirror coatings for the XUV is reviewed. Theoretically possible and experimentally achieved performances will be discussed.

VUV Laser Photolithography, J. C. White, H. G. Craighead, R. E. Howard, L. D. Jackel, and O. R. Wood II, AT&T Bell Laboratories, Holmdel, NJ.

An F, discharge laser at 157 nm has been used for the first time as an exposure source for high-resolution photolithography to achieve 150-nm features. Novel mask technologies and resist properties for VUV use are discussed.

5:15 PM TuC4

Diagnostics for an XUV/Soft X-Ray Laser, Robert L. Kauffman, Lawrence Livermore National Laboratory, Livermore, CA.

A transmission grating/x-ray streak camera spectrograph time resolves the spectrum from an XUV/soft x-ray laser. Its performance will be compared with other XUV instrumentation.

#### **TUESDAY, MARCH 6, Continued**

#### 1:00 PM POSTER SESSION

#### INVERSION INTO THE XUV

(Poster Paper)

ble Resonant Enhancement in Nonlinear Optical Freby Mixing, A. V. Smith, Sandia National Laboratories, juerque, NM.

nechanism of four-photon resonant enhancement of third onic generation is studied using two-input frequencies shown to lead to tunable resonant enhancements.

(Poster Paper)

ration of VUV Radiation in the Kilowatt Power Range to 130 nm by Stimulated Raman Scattering in Hydrogen, . Döbele, M. Röwekamp and B. Rückle, Fachbereich ik, Universität Essen GH, Federal Republic of Germany.

yields 13 tunable AS-lines from a green dye laser and 6 nes from 193 nm-radiation amplified in ArF. Quantitative surements of VUV-power are presented. Power at 130 nm aund 600 W.

(Poster Paper)

lent Generation of Tunable Radiation below 100 nm in ton, Keith D. Bonin, Mark B. Morris, and T. J. McIlrath, Inte for Physical Science and Technology, University of Iland, College Park, MD.

erent, tunable radiation below 100 nm was generated by a photon resonantly enhanced four-wave mixing process in ton. This radiation was used in conjunction with a highlution Fizeau wavemeter to scan the 11s' autoionizing nance in xenon.

1 (Poster Paper)

Ilmuously Tunable Sum-Frequency Generation Involving berg States, R. W. Boyd, D. J. Gauthier, J. Krasinski, and M. Malcuit, Institute of Optics, University of Rochester, hester, NY.

emely large values of the second-order nonlinear suscepty have been demonstrated in a system involving Rydberg as. The applicability of this technique to the extreme ultraft is discussed.

5 (Poster Paper)

Frequency Generation Spectroscopy of Rydberg States, Schnitzer, K. Hollenberg, and W. Behmenburg, sikalisches Institut I, Universität Düsseldorf, Düsseldorf, aral Republic of Germany.

w method for determination of Rydberg transition dipole ix elements from sum-frequency generation spectra is ented and applied to the principal series of Cd i.

#### **TUESDAY, MARCH 6, Continued**

TuD6 (Poster Paper)

Direct Measurement of a VUV Transition Oscillator Strength in Xenon, S. D. Kramer, C. H. Chen, M. G. Payne, and G. S. Hurst, Oak Ridge National Laboratory, Oak Ridge, TN.

The oscillator strength of the xenon 7s state was directly determined by measuring the phase-matching condition for four-wave mixing in xenon-argon gas mixtures.

TuD7 (Poster Paper)

High-Energy VUV Pulse Generation by Frequency Conversion, M. L. Diabal, J. Reintjes, and L. L. Tankersley, Laser Physics Branch, Optical Sciences Division, Naval Research Laboratory, Washington, D.C.

Third-harmonic conversion of XeF laser radiation at high pump energies is limited by absorption and breakdown. Improvements by phase matching will be discussed.

#### **XUV LASERS**

TuE1 (Poster Paper)

Time Evolution, Radial and Axial Distributions of the EUV Line intensities in Co<sub>2</sub>-Laser-Produced Plasmas, C. H. Skinner, C. Keane, H. Milchberg, S. Suckewer, and D. Voorhees, Plasma Physics Laboratory, Princeton University, Princeton, NJ.

We present spatially resolved measurements of excited state populations in  $CO_2$ -laser-produced plasmas that are candidates for laser action in the soft x-ray region.

TuE2 (Poster Paper)

Soft X-Ray Spectra, Population Inversions, and Gains in a Recombining Plasma Column, H. Milchberg, J. L. Schwob, C. H. Skinner, S. Suckewer, and D. Voorhees, Plasma Physics Laboratory, Princeton University, Princeton, NJ.

Time-integrated and time-resolved soft-x-ray and UV spectra have been measured from recombining  $\mathrm{CO}_2$  laser-produced plasmas. Determinations of population inversions and gain will be discussed.

TuE3 (Poster Paper)

Optical Pumping of Short-Wavelength Fluorescence in Plasmas Using Line Radiation, J. Trebes and M. Krishnan, Yale University, New Haven, CT.

Aluminum-ion line radiation pumps fluorescence in carbon ions in a plasma. Measurements of electron density and temperature enable comparison with a collisional-radiative model.

#### TUESDAY, MARCH 6, Continued

#### **3ENERATED X-RAYS**

#### Poster Paper)

By Source Based on a Low-Divergence, Highyn-Rate Ultraviolet Laser, E. A. Crawford, A. L. I, R. D. Milroy, and G. F. Albrecht, Mathematical Northwest, Inc., Bellevue, WA.

, using numerical modeling, that small-size plasmas d by a short-pulsed low-energy uv laser are potentially soft-x-ray sources.

#### Poster Paper)

Generated by Laser Irradiated High-Z Targets, X. ). Babonneau, D. Billon, J. L. Bocher, G. Di Bona, and , Commissariat a l'Energie Atomique, Centre d'Etudes il - Valenton, Villeneuve St. Georges, France.

suss the generation of x rays versus the target and atures by comparison of experimental data, simulample model, and scaling laws.

#### WEDNESDAY, MARCH 7, 1984

#### LASER GENERATED X-RAYS

David Nagel, Presider

#### 8:30 AM WA1 (Invited Paper)

Excitation of Metastable XUV Levels, R. G. Caro, J. C. Wang, J. F. Young, and S. E. Harris, Edward L. Ginzton Laboratory, Stanford University, Stanford, CA.

Excitation techniques are described that use x rays from a laser-produced plasma to create large densities of highly energetic metastable excited atoms and ions.

#### 9:00 AM WA2 (Invited Paper)

Photoionization Lasers Pumped by Broadband Soft X-Ray Radiation from Laser-Produced Plasmas, William T. Silfvast, Obert R. Wood II, John J. Macklin and Hans Lundberg, AT&T Bell Laboratories, Holmdel, NJ.

Broadband soft X-ray radiation from a laser-produced plasma has been used to produce large population inversions in Cd and Zn ions in the UV, visible and near infrared with inversion densities greater than  $10^{15}$  cm $^{-3}$  and gains as high as 40 cm $^{-1}$ .

#### 9:30 AM WA3 (invited Paper)

Dynamical Aspects of the Picosecond X-Ray Generation from Laser-Produced Plasmas, Hiroto Kuroda, The Institute For Solid State Physics, The University of Tokyo, Tokyo, Japan.

Systematic studies of the generation of picosecond x-ray pulses fromental dynam duced plasmas are performed experimental. The present understanding of dynam aspects of transient x-ray generations are reviewed.

#### 10:00 AM WA: (Invited Paper)

Experimen Simulation Studies on Soft X-Ray Emission from 0.53-µm Laser-irradiated Solid Targets, T. Mochizuki, T. Yabe, and C. Yamanaka, Institute of Laser Engineering, Osaka University, Osaka, Japan.

Soft x-ray emissions from 0.53-μm laser-produced plasmas of various Z targets have been experimentally investigated and compared with 1-D or 2-D computer-code simulation results.

#### 10:30 AM WA5

Measurements of Photoionization Cross Sections of Ions in the Extreme Ultraviolet, E. Jannitti, P. Nicolosi,\* G. Tondello,\* and Wang Yongchang,† Instituto Gas Ionizzati, CNR, Padova, Italy.

Measurements of photoionization cross sections from absorption spectra of He-like and Li-like ions of Be, B, and C obtained using two laser-produced plasmas are reported.

\*Istituto de Elettrotecnica ed Elettronica, Padova, Italy. †On leave from Northwest Normal College, Lanzhou, The People's Republic of China.

#### 10:45 AM COFFEE BREAK

#### **WEDNESDAY, MARCH 7, Continued**

**XUV LASERS** 

M. Richardson, Presider

11:15 AM WB1 (Invited Paper)

Amplification of Spontaneous Emission in Aluminum and Magnesium Plasmas, Pierre Jaegle, Laboratoire de Spectroscopie, Atomique et Ionique, Ecole Polytechnique, Cedex, France.

Amplification of spontaneous emission is observed for the 3d-5f transitions of Alio+ and Mgo+. Technical diagnostics and computational modeling are described.

11:45 AM WB2 (Invited Paper)
Population Inversion and Gain in Expanding Carbon Fiber Plasmas, G. J. Pert, Department of Applied Physics, University of Hull, Hull, England.

Carbon fibers of a few microns diameter heated by a Nd:glass laser pulsed offer a suitable medium for the generation of gain in the XUV spectral region. Population inversion occurs as recombination is induced by adiabatic cooling in the expansion of the hot fiber. Experimental results and their interrupation using computer modelling have given a good understanding of the underlaying physics and show two regeums of operation: one of high gain which places stringent limitations on the uniformity of illumination, the other, of lower gain, on the length of cylinderical focus.

12:15 PM WB3 X-Ray Laser Spectroscopy, R. C. Elton, R. H. Dixon, J. L. Ford, and T. N. Lee, Naval Research Laboratory, Washington, D.C.

Measured resonance-line emissions from various plasma ions are compared for photon pumping of x-ray lasers. Ne vii-ix laser-ion spectra will be shown.

12:30 PM CLOSING REMARKS

T. J. Mclirath

## AUTO-IONIZING AND MULTIPHOTON PROCESSES

Steve Smith, Presider

## MA7-1 Recent Experiments on Soft X-Ray Laser Development in a Confined Plasma Column\*

S. Suckewer, C. Keane, H. Milchberg, C. H. Skinner, and D. Voorhees

Princeton University, Plasma Physics Laboratory Princeton, NJ 08544

A series of recent experiments were performed with a new focussing system for our CO, laser, which allowed a significantly smaller focal spot. The plasma was created by the interaction of a lkJoule CO, laser with solid or gas targets. The plasma column was confined by a solenoidal magnetic field  $(B \approx 50-100 \text{ kG})$  or was expanding freely  $(B \approx 0)$ . Spectral line radiations in the VUV region were monitored by two instruments operating initially in the spectrographic mode (spectra) and later in the monochromatic mode (time evolution of line intensities). To increase the cooling rate of the recombining plasma column, higher-Z elements were introduced into the plasma. For example, in case of a gas target, oxygen, argon or xenon were added for faster plasma cooling. For solid carbon targets, Al-blades were used to increase radiation losses. Enhancement of hydrogen-like CVI 182A line intensity and population inversion in Li-like ions (CIV, OVI, FVII, and NeVIII) were monitored for different plasma conditions. In order to change these conditions we varied the amount of higher-Z elements, CO, laser power, magnetic field, and in the case of gas targets, we also varied the initial gas pressure. The interpretation of the time evolution, the radial and axial distribution of line intensities, together with computer simulations of the data will be presented.

ZONEPLATES AND THEIR APPLICATIONS IN SOFT X-RAY IMAGING.

Janos Kirz

Physics Department, SUNY at Stony Brook
Stony Brook, N. Y. 11794

Though the fabrication of zoneplates for XUV applications is not an easy task, and though the best zoneplates made to date are inefficient optical elements, these devices find important applications in soft X-ray microscopy where conventional lenses are unavailable. They are are also used as condensers and monochromators, and may even find a role in soft X-ray holography. We review the fabrication methods, the present state of the art and ideas for improvements in resolution and efficiency.

The scanning X-ray microscope operating at the National Synchrotron Lightsource uses a zoneplate fabricated by electron beam techniques at IBM. We shall discuss the capabilities of this instrument, its limitations, and some of the first results obtained with it.

the existence in the nucleus of nearly resonant intermediate states through which the multiphoton process can proceed. Whether such states generally do exist is the central issue being addressed in this work. Thus, it was first intended to demonstrate sum frequency generation in one case in which non-resonant intermediate states were known to exist. This was the case in which both initial and intermediate states were magnetic sublevels of the same nucleonic state and in which the transitions were mediated by a magnetic dipole, M1 operator.

Preliminary experimental efforts have been focused upon the generation of tunable multiphoton sidebands displaced by radiofrequencies in ferromagnetic materials. Intense sidebands on hyperfine components of the Mössbauer transition of <sup>57</sup>Fe near 0.09 nm were found to be maximized under conditions that minimized chances for spurious magnetostrictive effects. Prominent sidebands were observed at only tens of Watts of input power. A quantitative model was constructed that explains these results in terms of coherently excited nuclear states and confirms the estimates for matrix elements critical to the overall progress toward the broader tuning and stimulation of nuclear radiations.

This work was supported by the Office of Naval Research.

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Tunable Sub-Angstrom Radiation Generated by Anti-Stokes Scattering from Nuclear Levels

by

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This work concerns the demonstration of the feasibility of the tuning and perhaps even stimulation of nuclear radiation. Theory [1-3] has indicated that anti-Stokes Raman upconversion of intense but conventional long wavelength sources of radiation produced by scattering from isomeric states of nuclear excitation could lead to significant sources of tunable y-radiation characterized by the natural Mössbauer width of the lines. This would result in lines with sub-Angstrom wavelengths and widths of a few MHz. Further computations [4] have suggested that this type of coherent, as well as a new type of incoherent, optical pumping could even lead to appreciable levels of inversion of the population of nuclear levels that would be capable of supporting the growth of stimulated y-ray intensity. Whether or not these processes can reach threshold depends upon the resolution of basic issues lying in an interdisciplinary region between quantum electronics and nuclear physics that have not been previously addressed. It was the purpose of this work to study these issues experimentally.

The viability of this concept for the tuning of \gamma-radiation by adding the variable energy of a longer wavelength photon depends upon

#### MA4-1

Soft Xray Laser Experiments at the Novette Laser Facility

D. Matthews, P. Hagelstein, R. Kauffman, R. Lee, C. Wang, H. Medecki, M. Campbell, N. Ceglio, G. Stone, G. Leipelt, P. Lee, P. Drake, L. Pleasance, L. Seppala, W. Hatcher, G. Rambach, G. Heaton, R. Price, R. Ozarski, R. Speck, K. Manes, J. Underwood, A. Toor, T. Weaver, L. Coleman, B. DeMartini, J. Auerbach, R. Turner, W. Zagotta, A. Hawryluk, and M. Rosen

Lawrence LIvermore National Laboratory Livermore, California

We will summarize previous, as well as ongoing, work whose sole purpose is to demonstrate laser-pumped soft xray laser. We have concentrated our efforts on three possible laser schemes: 1) resonant photoexcitation, 2) collisional excitation, and 3) collisional recombination. Our earliest attempt only demonstrated a small gain of approximately 0.5-1 cm on the recombination scheme. Nevertheless, we have begun a multifaceted experimental program to determine what the crucial physics for all three schemes are, and where our experiments or predictions could have fallen short. We have combined our efforts with other facilities, such as KMS Fusion, Inc., where, with their Chroma Laser Facility, they are performing experiments to 1) test for line coincidences to 3 mA accuracy, 2) validating predicted density and temperature profiles using laser iterferometry and xray spectroscopy, and 3) testing the kinetics of inversion using a specialized experimental setup which is easily diagnosed, yet whose geometry closely resembles an xray laser target.

By the time of this conference we will be able to report the results of experiments conducted last winter at Novette, partial results from current experiments at KMS, and our plans for a new experimental series to be performed beginning April, 1984.

### Collisionally Excited XUV Laser and XUV Radiation from Autoionizing Levels of Potassium in Discharge

Valery O. Papanyan

Institute for Physical Research

Armenian Academy of Sciences, USSR

The talk will consider the application of quartet states of K to the construction of XUV lasers.

Experimentally, data for frquency tripling in a molecular gas, CO, will be described. The CO study provides insights into the effects of rotational cooling by supersonic expansion on the tripling process. The study also exploits the use of a two-photon resonance via the CO  $A^{1}II$  state to achieve high conversion efficiency. The  $1 \times 10^{12}$  photons per pulse generated at 98.5mm is two orders of magnitude better than the previously reported generation in an argon jet in this region of the spectrum.

There is significant interest in the use of VUV and XUV radiation to detect homonuclear diatomics such as hydrogen. A sensitivity of  $2 \times 10^8$  molecules per cubic centimeter per quantum state has been achieved using the laser-induced-fluorescence technique. Experiments are underway to compare this technique with the multiphoton ionization technique. Results of these experiments will be discussed.

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Pulsed Nozzle Techniques and Applications for the XUV (Invited)

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C. T. Rettner, E. E. Marinero IBM Research Laboratory 5600 Cottle Road San Jose, CA 95193

R. N. Zare Chemistry Department Stanford University Stanford, CA 94305

#### SUMMARY

It has recently been shown that the well-defined geometry of a gaseous beam, the cooling that results from a supersonic expansion, and the relative simplicity of a pulsed nozzle make a pulsed supersonic beam source most desirable in providing a simple scheme for gas-phase third harmonic generation of radiation to the extreme ultraviolet. A simple model has since been developed to describe the third harmonic generation process in a pulsed beam. The model employs three basic assumptions: first, that the gas density in the jet has a rectangular profile in the direction of propagation of the laser beam; second, that the length of the profile is determined by the conservation of particle flux through all planes perpendicular to the forward direction of the jet; and third, that the laser field is propagating in the plane-wave regime. Using this model, predictions on the functional dependence of the output on reservoir gas density, nozzle diameter, nozzle distance from the laser focus, and other gaseous medium parameters are obtained and are compared with results from experiments on frequency tripling to 118.2 nm in a xenon jet. Good agreement is obtained.

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The two-photon resonant enhancement of the induced polarisation provides considerable conversion efficiencies at input intensities which can be produced easily with pulsed laser systems. With the additional enhancement by appropriate autoionizing states VUV radiation could even be generated by sum frequency mixing of multimode continuous-wave (cw) laser light [8].

Single frequency cw coherent VUV radiation is now generated for the first time by tripling the frequency of a stabilized dye ring laser (Spectra Physics Model 380D) in Mg and Sr vapor [9]. Tuning  $\lambda_{\rm I}$  to the Mg two-photon resonance  $3^{1}S_{0} - 3^{1}D_{2}$  ( $\lambda_{L} = 430.88$  nm) a laser power  $P_{L}$  of only 0.2 W generated VUV radiation ( $\lambda_{vuv} = 143.6 \text{ nm}$ ) of more than  $1.\overline{2} \cdot 10^5 \text{ photons/sec}$  $(P_{VIIV} = 1.8 \cdot 10^{-13} \text{ W})$ . This output is close to the power expected from the results obtained with pulsed lasers [10]. In the range of  $P_1 = 90$  -200 mW  $P_{vuv}$  is proportional to  $P_L^3$  and the conversion shows no sign of saturation. In Sr resonant frequency tripling of the output of a Rhodamine 6G dye laser tuned to the  $4^{1}S_{0}$  -  $4^{1}D_{2}$  two-photon transition ( $\lambda_{L}$  = 575.8 nm) generated more than  $10^6$  photons at  $\lambda_{\text{VUV}}$  = 192 nm. An increase of the VUV output by at least one or even two orders of magnitude should be obtained at higher input power which will be achieved by placing the conversion cell into an external ring resonator. Continuously tunable radiation can be produced in Mg, for example, at  $\lambda_{\rm vuv}$  = 140 - 158 nm with two dye lasers operated at the wavelength  $\lambda_1$  = 430.88 nm and  $\lambda_2$  = 430 - 600 nm [11]. The expected VUV output of 10<sup>7</sup> to 10<sup>9</sup> photons/sec will be sufficient for spectroscopic applications. Because of the narrow line width and the very precise frequency control of cw laser systems the generated cw VUV will render possible linear laser VUV spectroscopy of highest spectral resolution.

In contrast to the sum-frequency the difference frequency can be generated in a medium with K  $\stackrel{<}{>}$  0 [1]. Since this conversion is not restricted by the dispersion of the medium it is of good advantage for the generation of VUV in the entire range between 105 and 200 nm. This was confirmed by the frequency mixing  $2\omega_{uv}-\omega_L$ ,  $2\omega_{uv}-\omega_{IR}$ ,  $2\omega_{uv}-\omega_L$  and  $2\omega_{uv}-\omega_{IR}$  (with  $\omega_{uv}=2\omega_L$  and  $\omega_{uv}'=\omega_{uv}+\omega_{IR}$ ) in the rare gases of Kr and Xe [5]. For these conversion schemes only one Nd-YAG laser-pumped dye laser system is required which is tuned in the operating range of the efficient DCM and Rhodamine laser dyes ( $\lambda_{I}=550-650$  nm).

At laser pulse powers of a few megawatts the efficiency of the nonresonant frequency conversion is typically  $10^{-5}$  to  $10^{-6}$ . Tuning the laser frequency to a two-photon resonance the resonant enhancement of the induced polarization can provide conversion efficiencies of  $10^{-3}$  to  $10^{-4}$  at input powers of only a few kilowatts.

The two-photon resonant frequency mixing has been investigated, for example, in Xe and Hg [6]. The experimental results provided tunable VUV of KW pulse power and detailed information on different saturation phenomena.

In Kr the lowest two-photon resonance 4p-5p [5/2,2] requires UV laser radiation at  $\lambda_R$  = 216.6 nm which can be generated by doubling the output of a blue dye laser ( $\lambda_L$  = 423 nm) in a deuterated KB5 crystal [7]. Because of the low conversion efficiency of 2-5·10<sup>-2</sup> the generated pulse powers P<sub>R</sub> are typically 60 - 150 KW. More powerful radiation is obtained by mixing the frequency doubled output of a Fluorescin 27 dye laser ( $\lambda_L$  = 544 nm) with the infrared of the Nd-YAG. The producable UV pulse power is close to 1 MW.

The mixing  $\omega_{\text{vuv}}=2\omega_{\text{R}}-\omega_{\text{L}}$  (with  $\lambda_{\text{L}}=270$  - 730 nm) generates widely tunable radiation. Tuning, for example, the dye laser in the range  $\lambda_{\text{L}}=540$  - 730 nm the conversions  $2\omega_{\text{R}}-\omega_{\text{L}}$ ,  $2\omega_{\text{R}}-(\omega_{\text{L}}+\omega_{\text{IR}})$  and  $2\omega_{\text{R}}-2\omega_{\text{L}}$  generate VUV at  $\lambda_{\text{vuv}}=127.5$  - 134.5 nm, 145.5 - 155 nm and 155 - 181 nm, respectively. Radiation at  $\lambda_{\text{vuv}}=135$  - 145 nm is produced by  $2\omega_{\text{R}}-\omega_{\text{L}}$  with  $\lambda_{\text{L}}=428$  - 548 nm which is in the tuning range of Coumarin dye lasers. At optimum conditions an input of  $P_{\text{R}}=200$  KW and  $P_{\text{L}}=1$  MW generated VUV pulses close to 0.5 KW.

#### Generation of Coherent Tunable VUV Radiation

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We report on the generation of narrowband tunable coherent Vacuum ultraviolet radiation by third-order sum- and difference frequency conversion of intense pulsed or continuous-wave dye laser radiation in rare gases or metal vapors.

Because of phase-matching conditions [1] the tuning range of the sum frequency is restricted to spectral regions of negative phase-mismatch  $\Delta K$  (defined as the difference between the wave vectors of the generated radiation and the driving polarization). Frequency tripling and sum frequency mixing in the rare gases Ne, Ar, Kr and Xe thus provided VUV radiation in those portions of the spectral region between 72 and 150 nm where these gases are negative dispersive [2], [3], [4].

In atomic gases the region of negative dispersion is not necessarily a narrow spectral range. For frequency tripling in Hg, for example, the mismatch  $\Delta K$  is negative in the range of 143 - 185 nm. Since  $\Delta K$  changes little in the major part of this range third harmonic and sum-frequency generation produces - at constant vapor pressure - widely tunable radiation. For dye laser radiation  $\omega_L$  ( $\lambda_L$  = 540 - 670 nm) the frequency mixing  $\omega_{vuv}$  =  $\omega_{uv}$  +  $2\omega_L$  and  $\omega_{vuv}$  =  $\omega_{uv}^{\dagger}$  +  $2\omega_L$  (where  $\omega_{uv}$  =  $2\omega_L$ ,  $\omega_{uv}^{\dagger}$  =  $\omega_L$  +  $\omega_{IR}$  and  $\omega_{IR}$  is the fundamental of the Nd-YAG laser which excites the dye laser system) provided VUV at  $\lambda_{vuv}$  = 143 - 167 nm and  $\lambda_{vuv}$  = 154 - 183 nm, respectively. Laser pulse powers  $P_L\approx 1.2$  MW,  $P_{uv}\approx 0.35$  M and  $P_{uv}^{\dagger}\approx 0.55$  MW generated VUV light pulses of 1 to 2 Watts. VUV of comparable output power has been generated in the same range by tripling the output of a Coumarin dye laser ( $\lambda_1$  = 430 - 550 nm).

# XUV GENERATION AND LASERS Robert P. Madden, *Presider*

#### MB1-1

#### Anomalous Multi-Photon Processes

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#### SUMMARY

Recent studies of multiphoton ionization indicate the presence of an anomalously strong coupling for high Z materials. The principal findings, obtained at intensities up to  $\sim 10^{16}$  W/cm<sup>2</sup>, are (1) an unexpectedly strong multiphoton coupling strength resulting in multiple ionization of target atoms, (2) a strong Z-dependence of the coupling, and (3) ion charge state distributions which in some cases resemble those characteristic of Auger cascades. The results of these experiments suggest, for the heavy materials, a multiphoton analog of the collective atomic inner-shell response observed in both single-photon photoionization and bremsstrahlung. The relatively slow decline observed in the abundance of high ion states as Z increases qualitatively corroborates such an interpretation.

coupled atomic shells is correct, strong radiation at short wavelengths is expected to be reradiated by the atom. Indeed, recently, in an experiment examining the properties of xenon and designed to detect XUV radiation, significant levels of spontaneous radiation have been observed in the region between 10 and 100 electron volts. The spectral width observed was determined by the 1500 Å aluminum filter used. The schematic of the apparatus used in these studies and the signal observed are shown in Fig. (1). The signal occurs precisely at the time of irradiation of the gas with the 10 psec 193 nm radiation, vanishes if the xenon flow is terminated, and is not observed if the xenon is replaced by other materials, such as krypton or hydrogen. All of these observations are consistent with the emission of XUV radiation originating from excited

#### MB1-2 XUV DETECTION ARRANGEMENT

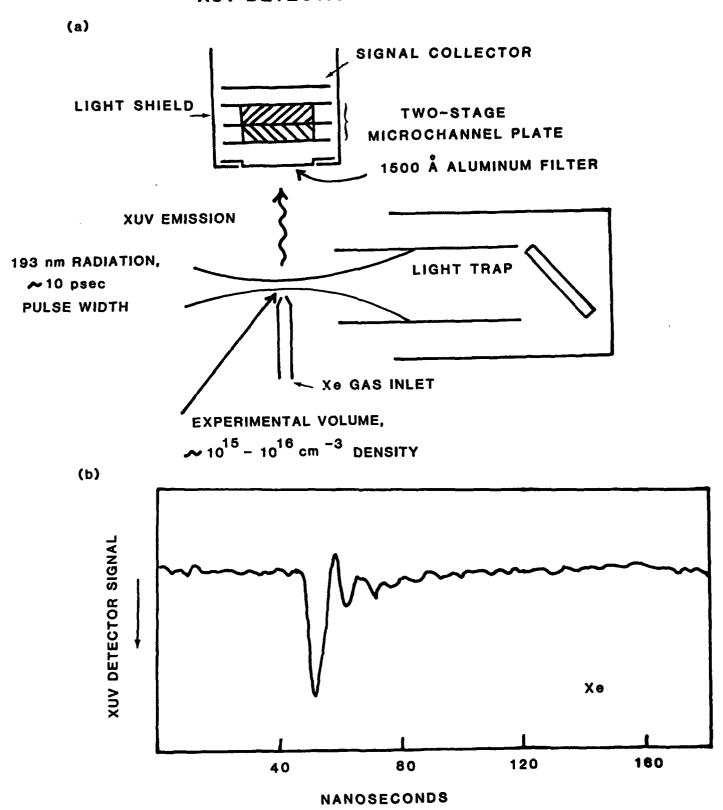


Fig. 1: (a) Experimental arrangement used to detect XUV radiation from highly excited atoms excited by 193 nm radiation at an intensity of  $^{\circ}$  10 -  $^{\circ}$  10  $^{\circ}$  W/cm<sup>2</sup>. (b) XUV signal observed from xenon in the 10 - 100 eV range; some ringing of the detector circuit is evident.

configurations of the xenon atom or its ions. Indeed, a 4d-excitation in these systems would be expected to radiate  $^6$  at  $^{\circ}$  70 eV, an energy near the peak of the transmission curve of the aluminum filter. Naturally, further experiments are being prepared to determine the spectrum of the observed emission.

The author wishes to acknowledge the valuable contributions of K. Boyer, H. Egger, T. S. Luk, and H. Pummer and the expert technical assistance of M. J. Scaggs and J. R. Wright. This work was supported by the Air Force Office of Scientific Research under contract number F49630-83-K-0014, the Department of Energy under grant number De ASO8-81DP40142, the Office of Naval Research, the National Science Foundation under grant number PHY81-16626, the Defense Advanced Research Projects Agency, and the Avionics Laboratory, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, Ohio

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MULTIPLY CHARGED IONS PRODUCED BY MULTIPHOTON ABSORPTION

A. L'HUILLIER, L.A. LOMPRE, G. MAINFRAY and C. MANUS

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Centre d'Etudes Nucléaires de Saclay, Service de Physique des Atomes et des Surfaces, 91191 GIF-SUR-YVETTE Cedex, France

The production of multiply charged ions induced by collisionless multiphoton absorption in rare gas atoms has been investigated using an intense 50 p sec laser pulse. Doubly charged ions are produced in helium and neon with a 1064 nm laser pulse in the  $10^{14}$  –  $10^{15}$  Wcm<sup>-2</sup> range. Up to Ar<sup>3+</sup> ions are produced in Ar, Kr<sup>4+</sup> ions in Kr and Xe<sup>5+</sup> ions in Xe with a 1064nm laser pulse in the  $10^{13}$  –  $10^{14}$  Wcm<sup>-2</sup> range. The laser intensity dependence of the production of multiply charged ions has been investigated for the five rare gases /1/. At least 146 photons, a value equivalent to 170 eV, have to be absorbed by a Xe atom at 1064 nm to explain the production of Xe<sup>5+</sup> ions. The basic absorption mechanism of so many photons by such multi-electron atoms is not yet well understood.

Doubly charged ions can be produced either by a simultaneous excitation of two electrons, or by a stepwise process via singly charged ions. These two processes take place at distinctly different laser intensities /2/. The production of doubly charged ions has been investigated in detail in Xe. The production of  $Xe^{2+}$  ions by a simultaneous excitation of two electrons is very sensitive to the laser wavelength. As an example, the proportion of  $Xe^{2+}$  to  $Xe^+$  ions decreases by a factor of 30 when the laser wavelength is changed from 1064 nm at  $10^{13}$  Wcm $^{-2}$  to 532 nm at  $10^{12}$  Wcm $^{-2}$ .

The theoretical one-electron model which has been used successfully to describe multiphoton ionization of atomic hydrogen and alkaline atoms in the past few years cannot be applied to describe the production of multiply charged ions induced by a collective response of an atomic shell irradiated by an intense laser pulse. Another model has to be developed to take into account electron correlation effects and possible electron rearrangement during the multiphoton absorption.

Finally, it would be of interest to take advantage of multiphoton ab-

sorption to selectively excite specific states of a singly or doubly charged ion, by tuning the laser wavelength. This could induce a population inversion and a stimulated emission in the 10 to 20 eV range.

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Laser Enhanced Auto-Ionization and Dressed Resonances\*

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Department of Physics and Astronomy University of Rochester Rochester, New York 14627

#### **Abstract**

We describe the strong field dressing of atomic resonance states, and apply the dressed state description to the photo-excitation of an auto-ionizing resonance, including the effects of radiative and purely transverse line broadenings.

#### Summary

We discuss the photo-electron spectrum and the depletion of the initial state predicted by a simple model for laser-enhanced auto-ionization. Our model consists of an initially populated bound state, one auto-ionizing state, one electronic continuum and a continuous-wave laser field of arbitrary strength. Also included are phase jitter relaxation, as well as spontaneous decay from the continuum ( and the auto-ionizing state) back to the ground state (coherent recycling). The model is exactly soluble, thus offering an opportunity to assess strong field effects and regimes of very rapid relaxation .

The analysis of the results is particularly simple and transparent in terms of "dressed resonances". These are a natural generalization of the usual dressed states appropriate for stimulated discrete-discrete transitions. A two-peak structure of the photo-electron spectrum reflects

the two dressed resonances in the model, i.e. the "elastic" and the "inelastic" resonances. In addition, the spectrum exhibits a Fano zero. The oscillatory-decaying behavior in time of the initial state population can be simply related to the electron spectrum in the dressed-resonance representation (DRR).

The effects of several types of relaxation are also evaluated. Recycling, being a decay to the ground state, increases the fraction of time the atom spends in its ground state. Correspondingly the elastic peak is narrowed while the inelastic one is broadened as the recycling-frequency parameter increases. Phase-jitter relaxation, on the other hand, broadens both elastic and inelastic peaks. This latter feature can be precisely stated in terms of a substitution rule. Both relaxations have therefore a competing effect on the ground state. We derive in the DRR a simple analytical expression for the photo-electron spectrum. Qualitative understanding of the various effects can easily be supplemented by a systematic analysis of the exact solution of the model in the different regimes of the physical parameter space.

<sup>\*</sup>Research partially supported by the U.S. AFOSR.

#### Planetrary Atoms

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Planetary atoms<sup>1</sup>, which have two highly excited electrons, are expected to exhibit new phenomena because the interelectron interaction can be as great as the central force which binds either electron. Angular correlations are expected to be particularly significant as the available phase space increases and as the e-e interaction becomes more anisotropic. We have used a four photon excitation technique<sup>2</sup> in conjunction with mass specific ionic detection to populate and identify msns, <sup>1</sup>S<sub>0</sub> states of barium having energies between 105,000cm<sup>-1</sup> and 114,000cm<sup>-1</sup>.

By varying n with m fixed (at 7, 9, 10 or 11) we have obtained quantum defects and reduced autoionization rates  $(n*^3\Gamma)$  for the msns Rydberg series. We find that the quantum defects increase linearly with m, but that the reduced autoionization rates are surprisingly independent of m!

For values of n nearly equal to m we observe a dramatic departure from expected behavior. The individual msns,  $^1S_0$  states are apparently very strongly mixed, predominately with high  $\ell$  configurations such as 6hnh,  $^1S_0$ . This mixing is evident as a pronounced modification of the excitation spectrum producing numerous

additional lines. Although semiclassical models can be used to explain some of the scaling rules, this enhanced mixing with high  $\ell$  states is not yet understood.

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# Multiphoton Ionization of Alkali Atoms

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# Summary

Multiphoton ionization (MPI) of alkali atoms has played a pivotal role in our understanding of the interaction of intense electromagnetic radiation with matter. The "hydrogen-like" energy levels and absence of low-lying autoionizing states make the alkali atom theoretically tractable. The low ionization potential of these atomic species and the ease with which one can produce atomic beams of alkali atoms facilitate the experimental studies. Many of the early MPI studies involved highpowered fixed-frequency lasers. Presently, the availability of tunable dye lasers with wavelength extension (i.e., frequency doubling, Raman shifting, etc.) makes it possible to study one- to six-photon ionization of the alkali atom with continuously tunable radiation. Also, harmonic generation in these systems which may be present during ionization can be recorded more easily than in other systems since the radiation generated is in the visible or near ultraviolet spectral region. The ability to tune the laser to high Rydberg states with even or odd numbers of photons accesses electronic states of both parities. Stepwise excitation is capable of selectively producing states of high

orbital angular momentum. Experiments in which highly excited states are produced in external electric or magnetic fields allow one to test fundamental ideas about the electron-Coulomb system in the quasicontinuum.

We will discuss recent experiments on one-, two-, and three-photon ionization of cesium and other alkali atoms. The angular distributions of the photoelectrons are compared with existing theory for the cases in which the first or second photon is resonant with one of the allowed transitions of the atom. Of particular interest is the case in which the third photon ionizes cesium atoms in excited nd states with high principle quantum number (n = 15 to 50). In this case, the ionizing photon photoionizes an almost "free" electron (highly excited Rydberg electron). We continue to measure these angular distributions into the That is, angular distributions are measured for the case where the electron is free ("free-free" transition). We are also able to measure angular distributions for nonresonant two-photon ionization of cesium just above the ionization threshold. The energy of the outgoing electron ranges from 0.03 to 0.1 eV. These angular distributions show a prominent peak at 90° in addition to major peaks along the laser polarization direction (0° and 180°). These studies of angular distributions for laser wavelengths above and below the twophoton ionization threshold provide a stringent test of the theory of MPI and above-threshold ionization.

Studies of MPI in the presence of an electric field (E = 5 to 3000 V/cm) in which the plane of polarization of the laser can be rotated relative to the direction of the electric field will also be described. The Stark effect mixes nearby states of different parity, allowing for

the detection of dipole forbidden states. For example, <u>np</u> states are easily detected in cesium by two-photon excitation. Interestingly, the relative intensities of the fine-structure levels appear to be close to the statistical ratio  $(^2P_{3/2};^2P_{1/2}=2:1)$  as contrasted with the well-known anomalous one-photon oscillator strengths.

It is also interesting to note that ms states are allowed under two-photon excitation but are only weakly observed in three-photon ionization spectra. This is due in part to the small photoionization cross section at these wavelengths. However, the application of an electric field mixes the nearby np and nd states thereby enhancing the ionization signal. For high n (20 to 30), it is possible to obtain np and ms signals as large as the md signals. Experiments in which the angle between the plane of polarization of the laser and the direction of the electric field is varied provide new and interesting information on the Stark effect on these states. Finally, we have observed structure in the two-photon ionization signal above the zero-field twophoton ionization limit for polarization parallel to the electric field. Such an effect has been seen previously in one-photon ionization studies. 3 For photon energies above the classical electric fieldinduced ionization limit, two distinct sets of structures are observed when the polarization is respectively parallel and perpendicular to the electric field. The separation between the first few peaks of each of the structures varies approximately as  $E^{3/4}$  although the separations between the peaks are strictly anharmonic. An E3/4 dependence has been found experimentally and predicted theoretically for the case of photoionization above the zero field limit (see Ref. 3). For the present two-photon ionization below the zero field limit, the spacings of each structure become closer together as the two-photon energy increases above the classical field-induced threshold. These two sets of oscillations may be related to the fact that the final angular momentum of the outgoing electron must be s or d wave. Finally, we note that the classical field ionization threshold is lower for the case in which the laser polarization and the electric field are parallel than it is when they are perpendicular.

Finally, the xenon chloride excimer laser is sufficiently powerful to completely ionize a beam of cesium atoms. The photoelectrons are produced by one-photon ionization with approximately 0.12 eV kinetic energy. It is possible to use these photoelectrons in a number of atomic physics problems, especially those involving electron-atom scattering in a laser field. Some of these applications will be discussed.

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<sup>&</sup>lt;sup>2</sup>Operated by Union Carbide with the U.S. Department of Energy under contract No. W-7405-eng-26.

<sup>&</sup>lt;sup>3</sup>See Richard R. Freeman, "International Conference on Atomic Physics, 1980," in <u>Atomic Physics 7</u> (D. Kleppner and F. M. Pipkin, Eds.), Plenum Press (1980).

# PHOTOIONIZATION OF EXCITED MOLECULAR STATES USING MULTIPHOTON EXCITATION TECHNIQUES

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Resonantly enhanced multiphoton ionization (REMPI) affords the opportunity to select a specific ionization pathway in order produce a particular ionic state for further study or to investigate detailed aspects of excited state photoionization dynamics. The electronic production of or vibrational state-selected ions using REMPI can be achieved by first preparing an intermediate Rydberg state that has a potential energy curve similar to that of the final desired ionic state, and ionizing the Rydberg state with a single additional photon. Under these circumstances, the Franck-Condon factors governing the final ionization step strongly favor the preservation of the Rydberg state core. Here we demonstrate the final

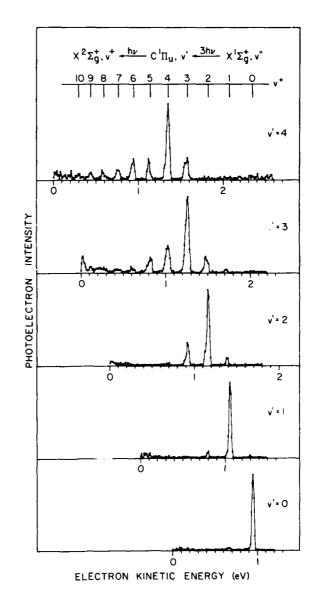


Figure 1. Photoelectron spectra following REMPI of  $\rm H_2$  via the C  $^{\rm I}\Pi_{\rm u}$ , v' levels.

# POSTER SESSION INSTRUMENTATION

Grotrian Diagram of Core-Excited Quartets in Na I

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# Summary

Using Hartree-Fock calculations and laser enhanced fluorescence experiments, we have identified 28 visible and near-UV Na emission lines as radiative transitions between core-excited states of Na I  $2p^53s3p$ , 3s4s, and 3s3d configurations. The resulting energy level diagram is consistent with these lines and two previously identified Na quartet lines at 3882 Å and 5071 Å. 1,2

Line assignments were based on Hartree-Fock calculations of quartet level absolute energies, autoionization rates and dipole transition rates. Predicted emission lines with reasonably strong branching ratios for photoemission were matched with previously unidentified lines observed in a pulsed hollow cathode discharge.

Because of metastable properties of the states  $2p^53s3p^4s_{3/2}$  and  $^4D_{7/2}$ , large population densities of these two lowest quartet states were produced in the discharge plasma. An intense dye laser was used to transfer population from these storage states to 3s4s and 3s3d quartet levels. Enhanced fluorescence from these levels was consistent with our line assignments.

<sup>&</sup>lt;sup>1</sup>H. G. Berry, R. Hallin, R. Sjodin, and M. Gaillard, Phys. Lett. <u>50A</u>, 191 (1981).

<sup>&</sup>lt;sup>2</sup>R. Frohlin and H. J. Andra, Phys. Lett. <u>97A</u>, 375 (1983).

MULTIPHOTON IONIZATION SPECTROSCOPY OF THE FLUOROMETHYL RADICAL

by

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Using mass resolved multiphoton ionization spectroscopy, we have detected the first electronic spectrum of the CH<sub>2</sub>F free radical. The CH<sub>2</sub>F radicals were produced in a discharge fast flow reactor<sup>1</sup> and introduced into a mass spectrometer's ion optics where they were irradiated with the tightly focussed output of a Nd:YAG pumped dye laser. CH<sub>2</sub>F radicals were first produced via the reaction of F + ketene. At laser wavelengths between 345-363 nm a spectrum was observed from m/z 33 ions. To identify the spectrum's carrier these experiments were repeated with the reaction, F + CH<sub>3</sub>F. Identical spectra were observed.

Major features of the spectrum are two triplet bands centered at 358 nm and 349.5 nm which represent (in two photons) a separation of 1560 cm<sup>-1</sup>. The spacing of the sub-bands within each of these triplets is ~155 cm<sup>-1</sup>. Several broad, weaker bands are also present. The most probable origin of these bands is a two photon resonance with a 3p Rydberg state (near 55700 cm<sup>-1</sup>) with a quantum defect of 0.56. After preparation of the Rydberg radical, absorption of an additional photon generates the ion--but with insufficient energy to cause ion fragmentation. No fragmentation was observed. Studies of the multiphoton ionization of CD<sub>2</sub>F radicals are underway to resolve the nature of the spectrum.

 $^{1}$ C. S. Dulcey and J. W. Hudgens, J. Phys. Chem.  $\underline{87}$  , 2296(1983).

Two and Three Photon Ionization of Cesium

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Probabilities for the two and three photon ionization of cesium are calculated using the density matrix formalism. We assume a narrow bandwidth radiation field of moderate intensity ( $10^8$  watts/cm<sup>2</sup>).

The various atomic parameters which enter the density matrix are calculated in the non-relativistic Hartree-Fock approximation. Results for two-photon Rabi rates, ground state two-photon ionization cross sections, excited-state single-photon ionization cross sections, and ground and excited-state A.C. Stark shifts are presented. Summations over intermediate states are handled by the inhomogeneous differential equation technique. Relativistic effects are estimated.

Our two-photon ionization cross sections for cesium are compared with recent experimental measurements.<sup>3</sup> Photoelectron angular distributions exhibit multiple minima when the radiation field is linearly polarized.

We investigate the influence of A.C. Stark shifts on the three-photon ionization of cesium near a two-photon resonance with the nd fine structure levels. Stark shifts are calculated as a function of principal quantum number and then compared with experiment. By numerical integration of the density matrix equations we also calculate the ionization line shape.

A.T. Georges, P. Lambropoulos and J.H. Marburger, Phys. Rev. 15, 300 (1977).

<sup>&</sup>lt;sup>2</sup> C.F. Fischer, "The Hartree-Fock Method for Atoms", (Wiley, New York, 1977).

<sup>3</sup> R.N. Compton, J.A.D. Stockdale, and A. Dodhy (unpublished).

180° and a subsidiary peak at 90°. We also observe that the ratio of the intensities at 90° to that at 0° (or 180°) decreases as the photon energy is increased. In addition to the slow electrons from two-photon ionization, an electron peak corresponding to three-photon absorption is also observed above the two-photon ionization threshold. The angular distribution for the photoelectrons produced by this "quasi-free-free" transition is sharply peaked at 0° and 180° and contains terms higher than  $\cos^2\theta$ .

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<sup>&</sup>lt;sup>2</sup>Operated by Union Carbide with the U.S. Department of Energy under contract No. W-7405-eng-26.

<sup>&</sup>lt;sup>3</sup>R. N. Compton, J.A.D. Stockdale, C. D. Cooper, X. Tang, and P. Lambropoulos, Phys. Rev. (in press).

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Multiphoton Ionization of Cesium Atoms Above and Below

The Two-Photon Ionization Threshold

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## Summary

The experimental arrangement consisted of a Nd:YAG pumped pulsed dye laser which was focused and crossed at right angle with a cesium beam. Photoelectrons were energy-analyzed by a spherical sector energy analyzer and detected with a dual multichannel plate.

Photoelectron angular distributions obtained for ionization of d states ranging from n=12 to n=21 by a two-photon resonant, three-photon ionization process, show maxima at  $\theta=0^{\circ}$  and  $180^{\circ}$ . The fine structure was not resolved and both  $D_{3/2,5/3}$  states were excited. The angular distributions are similar to those measured for lower d states. We will attempt to compare the angular distributions for large n to the simple predictions in which the photon energy is large compared to the electron binding energy (see Ref. 4).

Angular distributions have also been measured for the ultraslow electrons produced as the laser is tuned above the two-photon ionization threshold. In this process, the first photon lies nonresonant between the 6p and 7p levels. Angular distributions show maxima at  $\theta = 0^{\circ}$  and

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# POSTER SESSION MULTIPHOTON IONIZATION

# NOTES

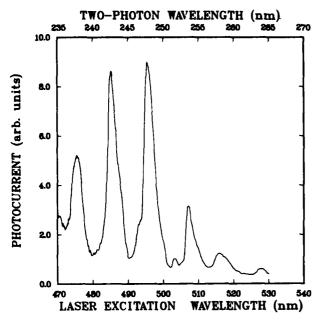


Fig. 1. The two-photon resonant three-photon ionization spectrum of the  $B_{2u}^{-1}$ 1g transitions of a  $10^{-3}$  mole dm<sup>-3</sup> solution of benzene in n-pentane at room temperature. The polarization of the laser beam is linear.

The high sensitivity of our multiphoton ionization conductivity technique (observed photocurrents  $\lesssim 10^{-14}$  A) combined with the fact that an ionization signal could be detected down to  $\lambda_{\rm exc} \lesssim 540$  nm indicates that the ionization threshold<sup>5</sup> of benzene in n-pentane is  $\lesssim 6.9$  eV. This upper limit is more than 2 eV lower than the gas phase value if a two-photon resonant three-photon inization is indeed the ionization mechanism. The possibility of a coherent three-photon ionization is being investigated.

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   Phys. Lett. <u>76</u>, 504-509.
- The ionization threshold of benzene in solution has not yet been reported.

Multiphoton Ionization of Benzene in Solution\*

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#### SUMMARY

Two-photon absorption and excitation spectra of benzene in liquid and rigid solutions have been frequently reported. 1 However, multiphoton ionization studies of benzene in liquid solution are limited and restricted to laser excitation wavelengths  $\lambda_{\rm exc} \lesssim 420$  nm, which correspond to two-photon excitation energies hv  $\approx$  6 eV. Using a laser conductivity technique suitable for liquid-phase ionization investigations, 2,3 we studied the multiphoton ionization spectrum of 10<sup>-3</sup> mole dm<sup>-3</sup> solutions of benzene in liquid n-pentane for  $hv_{exc} \lesssim 6 \text{ eV}$ . We observed for the first time that the structure in the photocurrent versus hv exc (see Fig. 1) spectrum reflects the linearly polarized spectrum of the  $B_{2n}-A_{10}$ transitions of benzene. Although we have not yet been able (due to the low intensity of our laser) to determine the order of the multiphoton ionization process, the spectrum in Fig. 1 is tentatively ascribed to a two-photon resonant three-photon ionization process. This spectrum is in excellent agreement with the two-photon excitation spectra reported by Friedrich et al.4

<sup>\*</sup>Research sponsored by the Office of Health and Environmental Research, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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a pump-and-probe method similar to that used in recent experiments on CF<sub>3</sub>NO.<sup>3</sup>

Glyoxal molecules cooled in a supersonic beam are dissociated by exciting specific transitions in the  $^{1}A_{u}$  +  $^{1}A_{g}$  manifold with a narrow-band, high energy pulsed dye laser. At a variable time following excitation of glyoxal, a tunable vacuum ultraviolet (VUV) laser  $^{4}$  is used to detect the CO product in a state specific manner by laser-induced fluorescence.  $^{5}$ 

The preliminary results of these experiments will be discussed both in terms of the elucidation of the detailed mechanism for glyoxal photochemistry, and in terms of the sensitivity and utility of using VUV laser-induced fluorescence for product detection in similar photofragmentation experiments.

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MB7-1 State to State Photochemistry of Glyoxal Using a Tunable

VUV Laser For Product Detection

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In recent years there has been much interest in how the initial state of a reactant affects the products in a chemical process. In order to answer this question, systems are needed which permit state-selective preparation of the reactants and state-selective detection of the products. One of the few systems in which state-to-state processes have been studied is molecular predissociation, due to the structured absorption spectrum of the excited state, which is coupled to unimolecular dissociation channels. This paper will discuss recent progress in studying the state-to-state dynamics of glyoxal (CHO-CHO) predissociation.

While both the spectroscopy and photophysics of the S<sub>1</sub> state of glyoxal have been extensively studied, its photochemistry is not yet fully understood. Along with formaldehyde, glyoxal stands as an important test case for theories of unimolecular photodissociation. A recent molecular beam study carried out by one of the authors has demonstrated the presence of photochemistry in the absence of collisions and provided detailed information on the branching ratios for different channels and on the microscopic fragmentation mechanism. However, other important questions about the state-to-state photochemistry can best be addressed by

electronic and vibrational state selectivity of REMPI by recording photoelectron spectra following single photon ionization of the  $2p\pi_{11}$  C  $^{1}\Pi_{11}$  Rydberg state of  $H_{2}$ (Figure 1) and the  $(1\pi_u)^3(3\sigma_g)^2$  $3s\sigma_{g} \circ_{3}^{1}\Pi_{u}$  Rydberg state of  $N_{2}$ (Figure 2). Both excited states were prepared by resonant three photon transitions from ground electronic state. In the case of  $H_2$ , the  $C^{-1}\Pi_{ij}$  Rydberg state converges to the ground electronic state of the ion, and

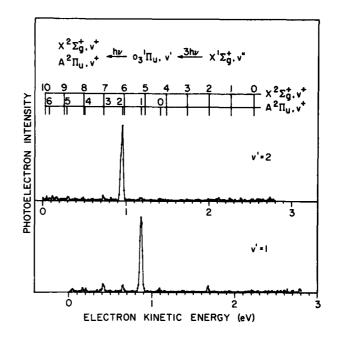


Figure 2. Photoelectron spectra following REMPI of  $N_2$  via the  $o_3$   $II_u$ , v' levels.

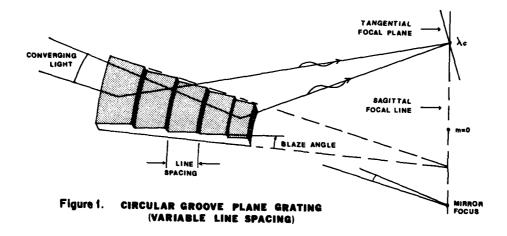
photoionization produces vibrational state-selected ions in the ground electronic state. In the case of N<sub>2</sub>, the o<sub>3</sub>  $^1\Pi_u$  Rydberg state converges to the first excited state of the ion, and photoionization produces vibrational state-selected ions in an excited electronic state.

The observed photoelectron branching ratios also reflect the dynamics of the excited state photoionization process. In particular, deviations from calculated Franck-Condon factors display the more subtle dynamical effects of the photoionization process. The present work provides exceptionally well-characterized, theoretically tractable results that demonstrate the degree to which Franck-Condon behavior can be expected in excited state molecular photoionization.

# POSTER SESSION INSTRUMENTATION

Variable Line Space Slitless Spectrometers at Grazing Incidence,

M.C. HETTRICK, U.C. Berkeley, Space Sciences Laboratory, Berkeley, CA 94720. A plano grating consisting of variably-spaced grooves concentric about a common point (fig. 1) provides  $\lambda/\Delta\lambda \sim 3000$  over a simultaneous factor two in soft x-ray wavelength ( $\lambda$  = 10-100 Å). The complete instrument contains a 1 arc sec 1-meter diameter collecting mirror whose 10 meter focal length includes a 1.5 meter spectrometer with an imaging detector having 15  $\mu$ m pixels. The end-to-end efficiency is approximately 4%, and the grating has a factor 4 variation in line spacing across a 50 cm ruled width.



A plano grating with grooves which radiate from a common point (fig. 2), i.e. an oriental fan, operates in the conical diffraction mount and is shown to have much lower spectral resolution due to dispersion limits imposed by geometric effects and attainable line densities. However, in the extreme UV ( $\lambda$  = 100-1000 Å), raytraces treating both equal and varied angular spacings indicate  $\lambda/\Delta\lambda \sim 2000-3000$  is attainable over a factor two in wavelength with high efficiency ( $\sim 10\%$ ).

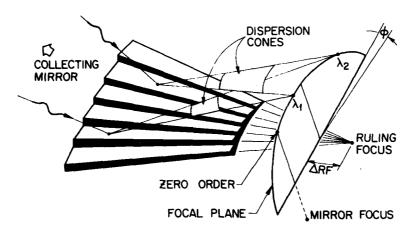


Figure 2. ORIENTAL FAN GRATING

An echelle spectrometer composed of the concentric groove grating and a fan grating cross-disperser is raytraced, revealing  $\lambda/\Delta\lambda \sim 20,000$  is achievable over a factor two in extreme UV wavelengths. The efficiency is  $\sim 2\%$ . Stigmatic ruling of either grating, provided by extreme UV holography, can obtain similar efficiency if the groove profiles are etched into triangles.

This work was supported by NASA contract NASW-3636 and NSF grant INT-8116729. This paper would not be appropriate for the poster session.

VUV Instrument Calibrations for Laser-Plasma Studies

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KMS Fusion has assembled a laboratory soft x-ray calibration system, which enables a quick response to the needs of laser-plasma experiments. Interest in laser-generated VUV sources has grown from the early work of W. Ehler in 1968 to the detailed line identification studies of J. Reader (NBS). Simultaneously, there has been a dramatic growth in the development of instrumentation for both spectroscopy and detection of 50 eV to multi-keV radiation. Calibration of these instruments, however, has frequently lagged behind their introduction, limiting our ability to accurately interpret their data. This has occurred because typical calibration sources are expensive and/or labor intensive and suffer from an inability for fast turnaround. Our source has become both flexible and capable, presently allowing calibrations in wavelength and intensity from 67.4 Å to 2.76 Å with Ka and La sources.

The KMSF system utilizes a Manson, Inc. 5 W point x-ray source with a flowing gas proportional counter and a Nuclear Data 62 MCA. The schematic of Figure 1 demonstrates that intensity calibration can be performed in real time.

Successful techniques of calibration include appropriate spectral filtering of the source and careful control of the proportional counter count rate. These techniques will be described as they were applied to the calibration of a grazing incidence spectrograph, an x-ray diode, and photographic film.

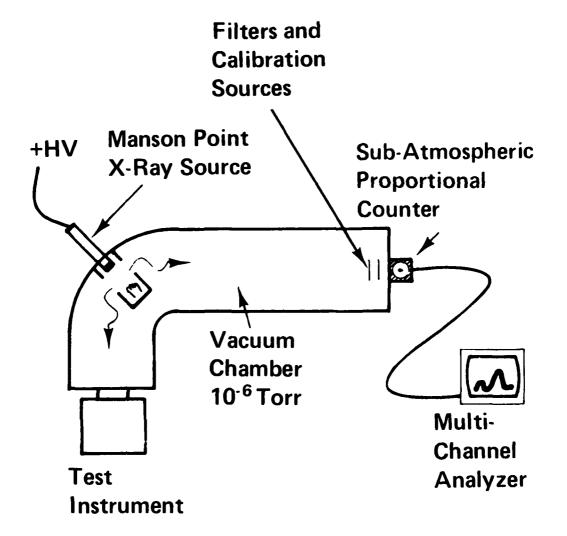


Fig. 1

A High-Resolution VUV Spectrometer with Electronic Parallel Spectral Detector

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We demonstrate a new high resolution VUV spectrometer for applications in the range 50 to 800Å. The instrument is comprised of a laser-plasma VUV source, which provides continuum background illumination, a 1.5m grazing incidence spectrometer, and a 1024-channel VUV optical multichannel analyzer (VUV-OMA). The VUV-OMA is of new design, featuring a special resolution-enhanced channel electron multiplier array in an overall configuration chosen to optimize the spatial resolution of the detector while maintaining single-photoelectron sensitivity.

In addition to bringing the advantages of linear response parallel spectral detection to general VUV photoabsorption studies of atoms, molecules and thin solid samples, the instrument has the special capability of performing time resolved spectroscopy on transient species. The characteristics of the source and detector along with various applications of the instrument to atomic physics will be discussed.

# Photoemissive Materials for 0.35µm Laser Fiducials in X-ray Streak Cameras\*

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#### **SUMMARY**

The Lawrence Livermore National Laboratory's laser fusion program makes extensive use of soft x-ray streak cameras for the diagnosis of laser irradiated targets. The capability of simultaneously recording the laser pulse and the x-ray flux in the streak camera will enhance the utility of the instrument. A program is under way to identify photocathode materials able to photoemit efficiently for soft x-rays (sub-Kev) and the  $0.35\mu m$  (3.5ev) wavelength of the future NOVA fusion laser facility.

An important requirement of such a photocathode is that it can withstand exposure to atmosphere without degradation of performance. Consequently, particular emphasis was devoted to metallic photocathode materials with low work functions. Such materials were thin-film deposited on transparent substrates identical to those used for x-ray photocathodes.

A well characterized 0.35µm wavelength laser source of 40 picosecond pulsewidth was obtained by frequency tripling the output of a small Nd:YAG laser system. Calibrated photodiodes monitored laser energy at the cathode surface and the x-ray streak camera output was recorded on film.

A number of materials suitable for this application have been identified. Several methods of providing a laser fiducial network are described.

# MD5-1 X-UV GAIN AMPLIFICATION STUDIES IN LASER PLASMA USING NORMAL INCIDENCE MULTILAYERS MIRRORS

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# SUMMARY :

Progress achieved in X-UV Amplification of Spontaneous Emission (ASE) lead us to look as soon as possible for mirror cavity feasability.

Recent measurements achieved about ASE observed with different lengths of plasma ( $\lambda \simeq 1$  cm) (1) enable us to face \*\*xperiments withlonger medium as well as to test directly the use of mirrors available for an X-UV laser cavity.

Normal incidence multilayer mirrors, especially optimized in the X-UV range, are expected to provide reflectivity from 30 to 80 %  $^{(2)}$ . According to current measurements, a 20 % to 30 % reflectivity efficiency is a realistic prediction around  $\lambda \simeq 100$  Å, in the present state of art in multilayering.

Set behind the plasma a single mirror having this reflectivity return enough light through amplificating medium for making it possible an observable change in the spectrum. The band pass of the mirror has to be centered at the desirated wavelength.

Calculations for a two mirrors cavity show that such a device should be at once a very good help in amplification diagnostic even with a plasma of a few millimeter long.

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- (2) A.E. ROSENBLUTH Thesis University of Rochester (N.Y.) 1982.

# PERFORMANCE OF TRANSITION METAL--CARBON MULTILAYER MIRRORS FROM 80 TO 350eV

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We have measured the reflectivity of transition metal (Co, Fe, V, and Cr)-carbon multilayer mirrors between 80 to 350 eV. The multilayer structures were fabricated by electron beam evaporation with <u>in situ</u> monitoring during the deposition process in order to maximize the reflectivity of the coating. The effective 2d spacing of all the samples was approximately 150 Å.

The experiments were performed with a grazing incidence type monochrometer at the Stanford Synchrotron Radiation Laboratory. An independent  $\theta$  (sample) and  $2\theta$  (detector) measurement system was used. The sample and detector were fixed and the S-polarized photon energy was scanned.

Peak reflectivities of 20% were measured at 160 eV ( $\theta$  = 30°) and 5.5% at 84 eV ( $\theta$  = 75°). The carbon in the samples severely degrades their performance near the carbon edge. The resolving power (E/ $\Delta$ E) of these samples was 18. These results can be compared to simple computer calculation.<sup>2</sup> The resolving powers can be predicted quite accurately, but the experimental reflectivities are typically lower

lower than calculations by up to 50%. Many effects, including surface roughness, uncertainties in the optical constants, and diffuse boundaries between the layers could contribute to this discrepancy.

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# **XUV SPECTROSCOPY**

James J. Wynne, Presider

LASER SPECTROSCOPY EXPERIMENTS ON ATOMIC AND MOLECULAR HYDROGEN

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H-Atom: The two-step excitation-ionization,

$$H(n=1) \xrightarrow{VUV} H(n=2) \xrightarrow{(\pi \text{ or } \sigma)} H^{*} + H^{+} + e$$
,

has been studied in electric fields (1-8 keV/cm) using linearly polarized ( $\pi$  or  $\sigma$ ) VUV and UV laser light. Tuning the VUV to selected components in the (n=2) Stark manifold and scanning the UV, the H\* excitation energy ranged from ~500 cm<sup>-1</sup> below to ~100 cm<sup>-1</sup> above the zero-field ionization potential, IP<sub>o</sub>. Ionization spectra taken for  $(\pi,\pi)$ ,  $(\pi,\sigma)$ ,  $(\sigma,\pi)$ ,  $(\sigma,\sigma)$  polarization, showed the sharp line structure from states between the field-ionization saddle point energy and the IP<sub>o</sub>, in agreement with theory (Fig. 1). In the  $(\pi,\pi)$  case oscillating resonances extending beyond the IP<sub>o</sub> were observed. As an example, Fig. 1 shows the ionization spectrum for  $(\pi,\pi)$  excitation at field strength F = 5714 V/cm. The lines are identified by upper state parabolic quantum numbers  $|n_1,n_2,|m|>$  with  $n=n_1+n_2+|m|+1$ . Lifetimes of the field ionizing states have been measured and the dependence of the oscillations on the electric field has been studied.

 $H_2$ -Molecule: a) State-selective excitation of  $H_2(X^1\Sigma_g^+)$  to  $H_2(B^1\Sigma_u^+)$  has been investigated with tunable VUV from ~1120 to ~1060 Å, employing (B-X)-fluorescence and/or photoionization,  $H_2(B^1\Sigma_u^+) + UV + H_2^* + H_2^+ + e$ , with fixed frequency UV, for detection.

b) Preparing selected J-levels in the  $(B^1\Sigma_u^+, v=0)$  state, dissociation and ionization from these levels has been studied by scanning the UV light.

# TuAl-1

# Molecular Dynamics Probed by VUV Radiation

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Laser-induced fluorescence has proved to be a powerful tool for the study of inelastic collisions in gases and at surfaces. Joys and sorrows experienced in the attempt to extend such measurements into the VUV will be discussed and exemplified.

### TuA3-1

# OF SYNCHROTRON AND LASER RADIATIONS FOR PRESENT AND FUTURE IONIZATION

## STUDIES IN EXCITED ATOMS AND IONS

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The study of photoionization processes in excited atoms requires the of two different photon sources: the one to prepare the atoms in specinitial states and the other one to photoionize these excited states. The advent of high-power frequency-tunable lasers, it has been possite to prepare a sizable stationary fraction of valence excited atoms and laser-ionize these laser excited states. However, available laser energy and tunability ranges have restricted these experiments to outer electors of alkali- and alkaline-earth atoms. In some atoms placed into excitates by means of a pulsed laser, inner-shell photoabsorption has been idied by using ultraviolet continuum radiation from a BRV source.

The broad energy spectrum of synchrotron radiation was an obvious invition to extend these earlier measurements. After the first observation of ter-shell photoionization in laser-excited atoms by synchrotron radiation, tensive studies have been carried out, using a cw ring dye laser to creathe excited states and the synchrotron radiation from the ACO storage to probe inner -outer shell photoionization and autoionization in the exemption at the present status of these experiments will be presented.

The intensity of synchrotron radiation can be greatly enhanced and its ctral distribution modified through the insertion of undulators in a aight section of a storage ring. The generation of stimulated radiation recently been achieved in the first successful operation of a storage of the electron laser. Other experiments are in preparation, such as production of coherent VUV radiation by bunching the electron beam of an itical klystron, using a high-power Nd Yag laser. These new devices will fer the opportunity to greatly extend the experiments on excited atoms and secules, in several ways: they could be used either to produce excited

Vacuum Ultraviolet Photoionization of Cold Molecular Beams:
Single and Multiphoton Ionization and Photoelectron Spectroscopy

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### Summary

A versatile apparatus for the study of vacuum ultraviolet (VUV) spectroscopy and photoionization of molecules has been developed. A pulsed, supersonic molecular beam is crossed that the focused beam of a pulsed dye laser or its doubled or tripled output. Ions are created by multiphoton ionization (MPI) with the fundamental beam (three to five photons), two-photon ionization using the doubled or tripled beam, or one-photon ionization with VUV. Use of a second laser for two-color experiments is also possible.

The ionization event is monitored by time-of-flight mass spectrometry and by photoelectron energy analysis. The latter neasurements use a dispersive spherical sector electron energy analyzer. This apparatus thus combines our previous work on VUV spectroscopy of high-pressure gases using nonlinear optical techniques with fragment ion and photoelectron analysis extensively used for MPI experiments on effusive beams. The addition of the supersonic molecular beam allows examination of vibrationally and rotationally cold monomer beams as well as molecular clusters.

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#### TuA6-1

#### SPECTROSCOPIC STUDY OF Xe DIMER USING VUV LASER EXCITATION

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Several studies of the absorption and emission spectra of Xe dimers ve been reported using cold vapor and large grating spectrographs  $^{1,2,3}$ . me vibronic structure was discernable in the band systems at 130 and 149 nm sociated with the first two resonance lines of Xe. Analysis has led to iformation on the potential well-depths of both  $0^+_1$  excited states.

We wish to report on preliminary results obtained from laser fluorescence-ccitation spectra of Xe dimers. The dimers were produced in a pulsed upersonic jet and probed with coherent, tunable radiation generated by 4-ive-sum-mixing in Mg and Zn vapors<sup>4</sup>.

Gas mixtures of 5% Xe in He resulted in strong rotational cooling ( $\sim 10^{\circ}$ k). nus new resolved features have been observed in both 130 and 149 nm band systems.

Eight bands were observed around 149 nm which were spaced by  $\sim 50$  cm<sup>-1</sup>. ach band contained  $\sim 10$  features, each having a width of  $\sim 2.5$  cm<sup>-1</sup> and separated rom each other by  $\sim 4$  cm<sup>-1</sup>.

More than 11 strong features were observed near 129.6 nm, ( $\sim$ 16 cm<sup>-1</sup> VHM) with an average spacing of  $\sim$ 35 cm<sup>-1</sup>. We are now attempting to analyze hese spectra.

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The uncertainty is estimated to be less than 30%. This method can also be used to count isotopically selected zenon atoms. Assuming it is possible to generate about 100 nJ of vacuum ultraviolet laser beam at 1067 Å or 1048 Å argon atoms can also be counted at low levels.

This research was sponsored by the Office of Health and Environmental Research, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

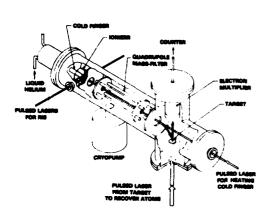


Fig. 1. Schematic of experimental method for counting noble gas atoms with isotopic selectivity.

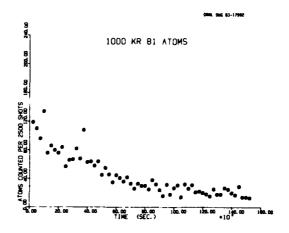
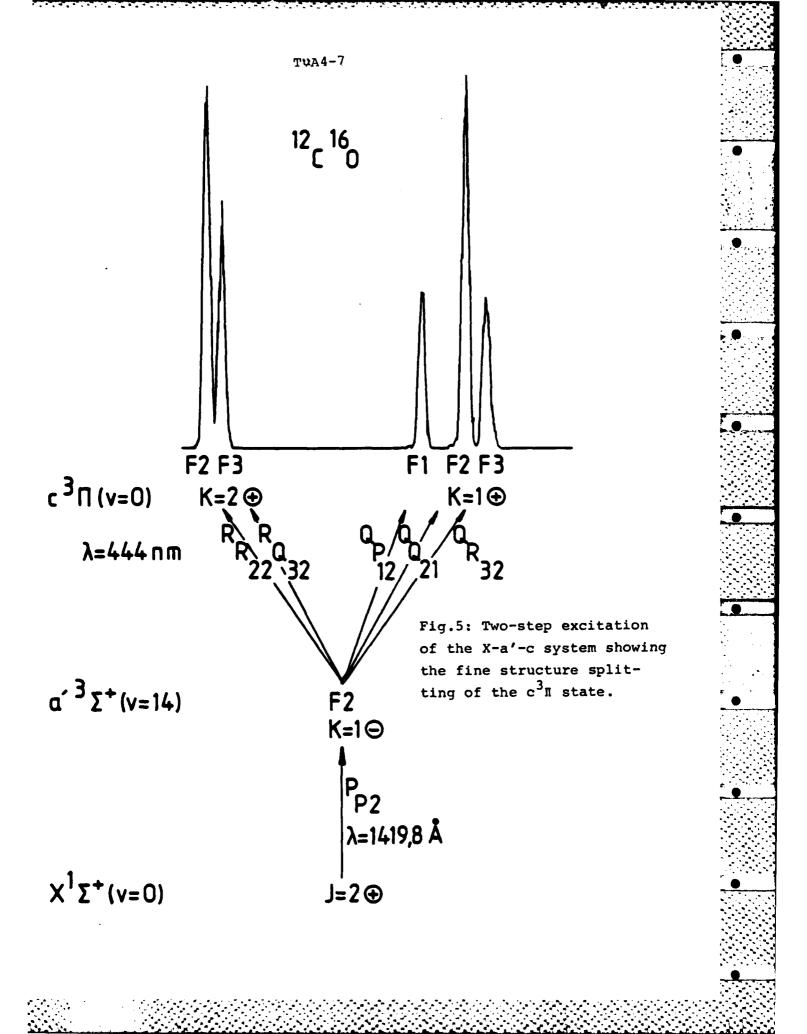


Fig. 2. Experimental results on counting 1000 atoms of <sup>81</sup>Kr.

81Kr Detection Using Resonance Ionization Spectroscopy

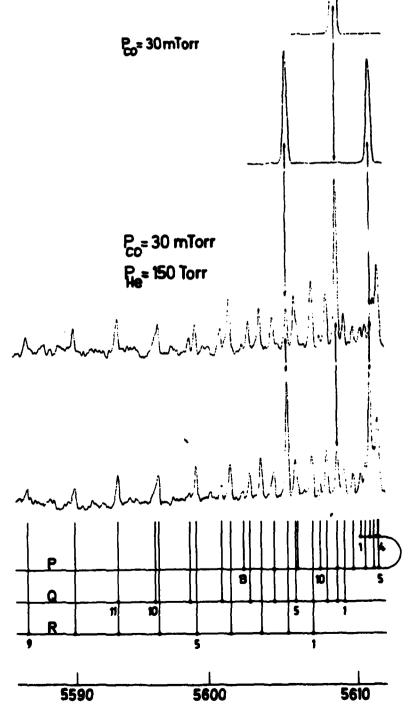
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The technique of resonance ionization spectroscopy (RIS) was extended to develop a means for counting individual atoms of a selected isotope of a noble gas. The experimental schematic is shown in Fig. 1. The concept for counting noble gas atoms with isotopic selectivity utilizes a laser for ionizing atoms of a selected atomic number (Z) and a mass spectrometer for atomic mass (A) selection. After atoms have been selectively ionized and mass selected, the ions are accelerated to 10 kV onto a Be-Cu target where they are implanted. The target will emit a pulse of several electrons which are detected by an electron multiplier. A four-wave mixing scheme was used to generate a 1165 Å beam with energy of 500 nJ/pulse. Thus, krypton atoms could be efficiently excited by resonant radiation and subsequently ionized. The use of a one-photon excitation step rather than a two-photon step also reduces the off-resonant multiphoton ionization background. An atom buncher was developed to enhance the probability that krypton atoms will be in the ionization laser beam at the time of the laser pulse, enabling a sample of 81Kr atoms to be counted in about 1 hr. Experimental data for counting 1000 atoms of <sup>81</sup>Kr are shown in Fig. 2. The detection limit is believed to be less than 300 atoms of 81Kr.



## (0-3) band of the CO $B^1\Sigma^+$ - $A^1\Pi$ system

Fig.4: Two-step excitation of the X-A-B system in CO for the collision free case at low pressures and for the high pressure case showing collision induced transitions in the second excitation step.





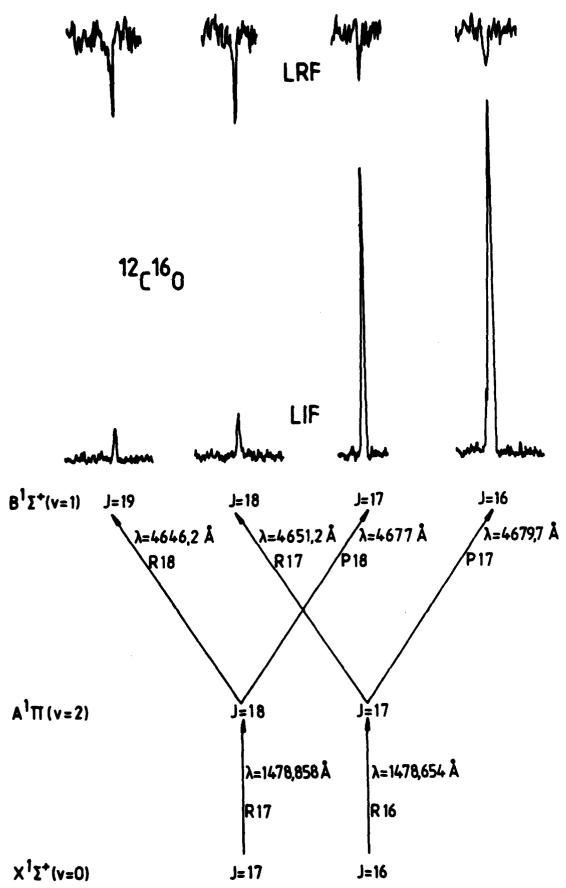
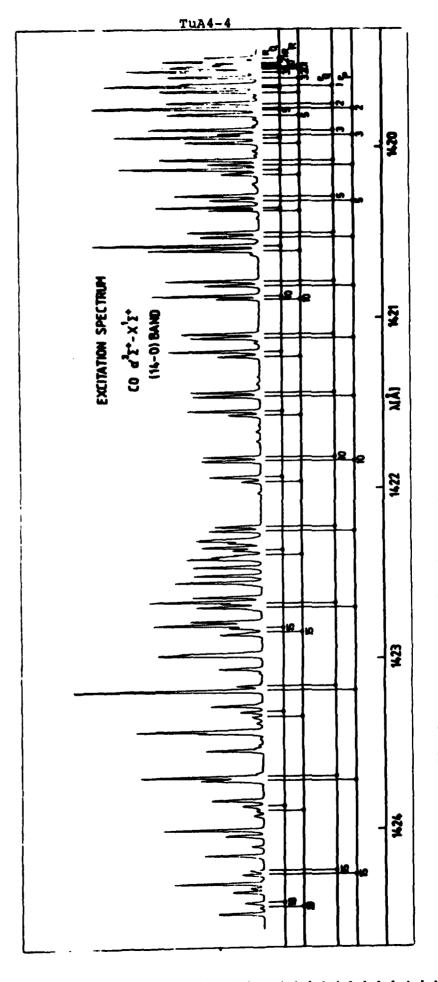
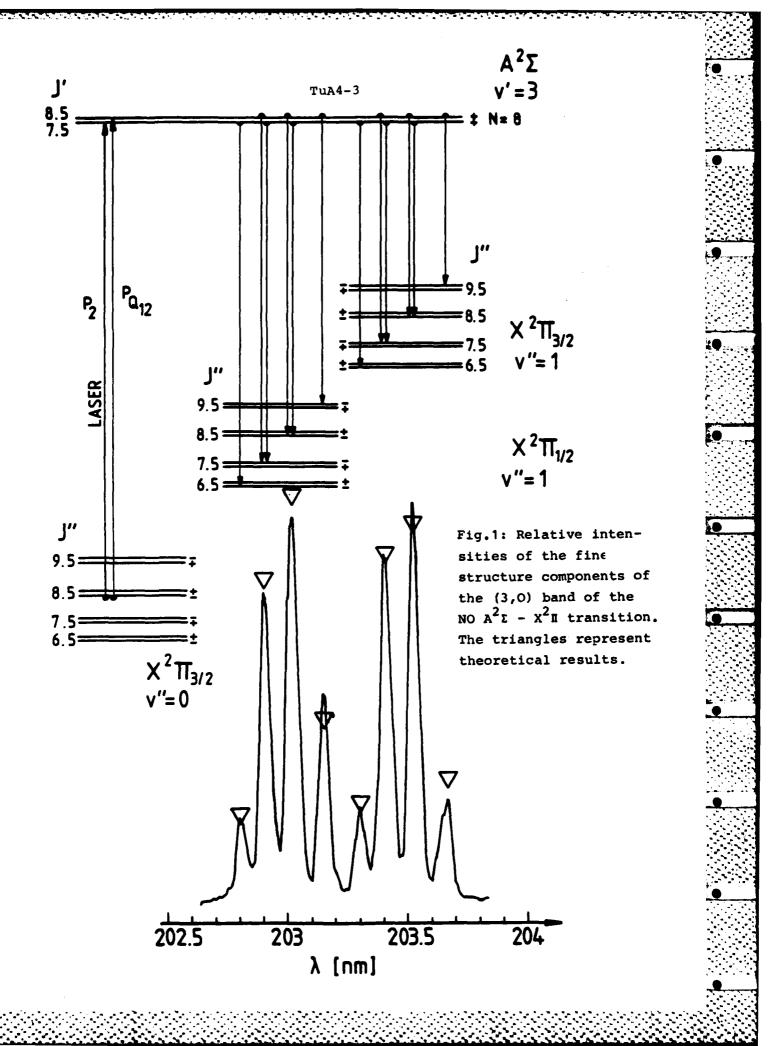


Fig.3: Two-step excitation of the X-A-Bsystem in CO showing the onset of the predissociation by a strongly reduced fluorescence.



of the A I - X I + system which covers the same spectral region and Fig.2: Frequency selective excitation spectrum of the (14,0) band -  $X^{1}\Sigma^{+}$  system. The superimposed strong (4,0) band fluoresces in the vacuum uv, has been completely suppressed by detecting only the infrared fluorescence. of the CO a'3r+



Using excimer or nitrogen laser pumped dye lasers coherent vacuum uv sources (spectral region: 120-200 nm, line width: 0.1-0.3 cm<sup>-1</sup>,  $10^{11}-10^{12}$  photons per shot, repetition rate  $\leq 100$  sec<sup>-1</sup>) are employed for testing novel techniques of laser spectroscopy in the vacuum uv.

Pumping individual rotational vibrational levels of the NO  $A^2\Sigma$  state, the J-dependence of the Franck Condon factors and of its individual fine structure components are shown to be in good agreement with theory revealing the transition from Hund's coupling case (a) to case (b).

Detecting the infrared fluorescence between the excited triplet states of the CO molecule frequency selective excitation spectroscopy has been carried out on the singlet-triplet intercombination bands in the vacuum uv. Several bands of different intercombination systems have been measured whose spectra are completely free from the superimposed bands of the A-X system whose transition moment is larger by three orders of magnitude. The A-state fluorescences in the vacuum uv.

Using a spectrometer as a filter for the optical detector the technique of frequency selective excitation spectroscopy was also used to separate the A-X from the B-X system of the NO molecule. This is achieved by alternately measuring the strongest fluorescence bands of either system. In this manner many new lines of the weaker B-X system have been identified.

State selective vacuum uv-visible double resonance spectroscopy was realized on the CO molecule by a two-step excitation method. In the first step individual transitions of the allowed or forbidden bands have been pumped in the vacuum uv. In the second step a visible laser pumps a transition from the intermediate state to a higher excited state of the molecule. In this manner we have reanalyzed the predissociation of the  $B^1$   $\Sigma^+$  state, we have investigated collision induced transitions in the  $A^1$  state and we have measured the fine structure splitting of the  $c^3$  state from the line positions of the  $c^3$   $\Gamma$  -  $a^{1/3}$   $\Sigma^+$  system.

states requiring higher excitation energies than presently available from classical laser sources, or to photoionize excited atoms with lower densities. Also, with the next generation of synchrotron radiation facilities, starting with SUPER ACO in Orsay, it may become possible that a synchronously pumped dye laser matched to the repetition frequency of a storage ring would provide the possibility to develop dynamical studies in time-resolved experiments. Finally, with the new sources of multiply charged ions nowadays available, photoionization experiments on ions, either in the ground state or in some excited states, could become feasible, using undulator and laser radiations.

The opportunities opened up by these future electron/positron -storage ring based sources of VUV and soft x-ray radiation will be discussed.

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#### State-selective vacuum uv spectroscopy of small molecules

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State-selective spectroscopy of the CO and NO molecule is demonstrated using the methods of fluorescence-, of frequency-selective excitation, and of vacuum uv-visible double resonance spectroscopy.

The total excitation energy ranged from the dissociation limit for H(n=1) + H(n=2) at ~850 Å to >804 Å, the adiabatic IP. Non-mass specific detection of ions  $(H^+, H_2^+)$  and electrons was used. The dissociation  $H_2^+ + H(n=1) + H(n=2)$  was observed via photoionization of the excited H-atoms,  $H(n=2) + UV + H^+ + e$ , simultaneously with  $H_2^+ + H_2^+ + e$ . Figure 2 shows, as an example, a section of the dissociation/ionization spectrum from the  $(B^1 \Sigma_u^+, v=0, J=1)$  state. The marks N = 0, 1, 2 and 3 indicate the ionization energies for  $H_2^+ + (I_2^+, V=0)$  in the respective rotational levels.

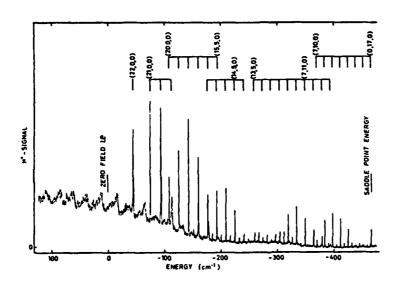


Figure 1

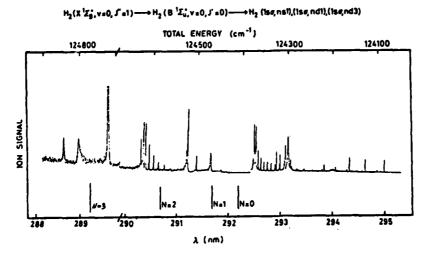


Figure 2

This paper will describe experiments designed to demonstrate and test the various capabilities of this new apparatus. These will include one-, two-, and four-photon ionization experiments on nitric oxide emphasizing photoelectron spectroscopy. Progress will be reported on experiments combining photoionization, photofragment, and photoelectron spectroscopy in studies of a number of polyatomic molecules.

Operated by Union Carbide with the U.S. Department of Energy under contract No. W-7405-eng-26.

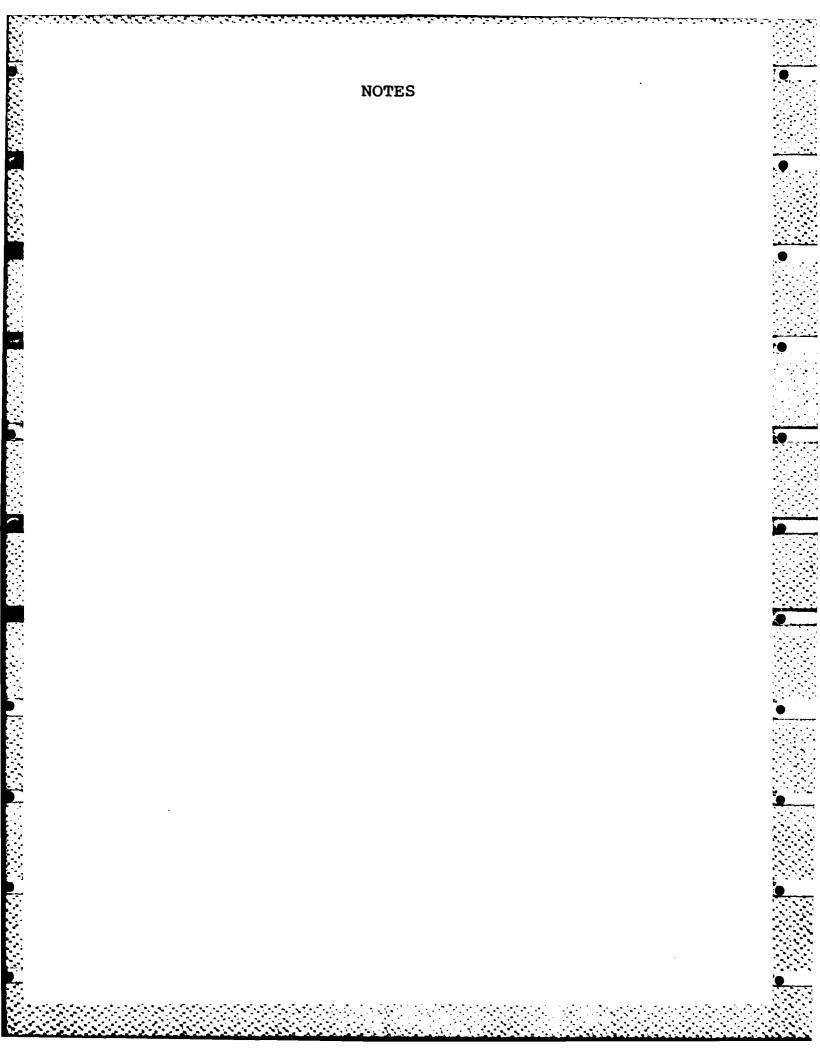
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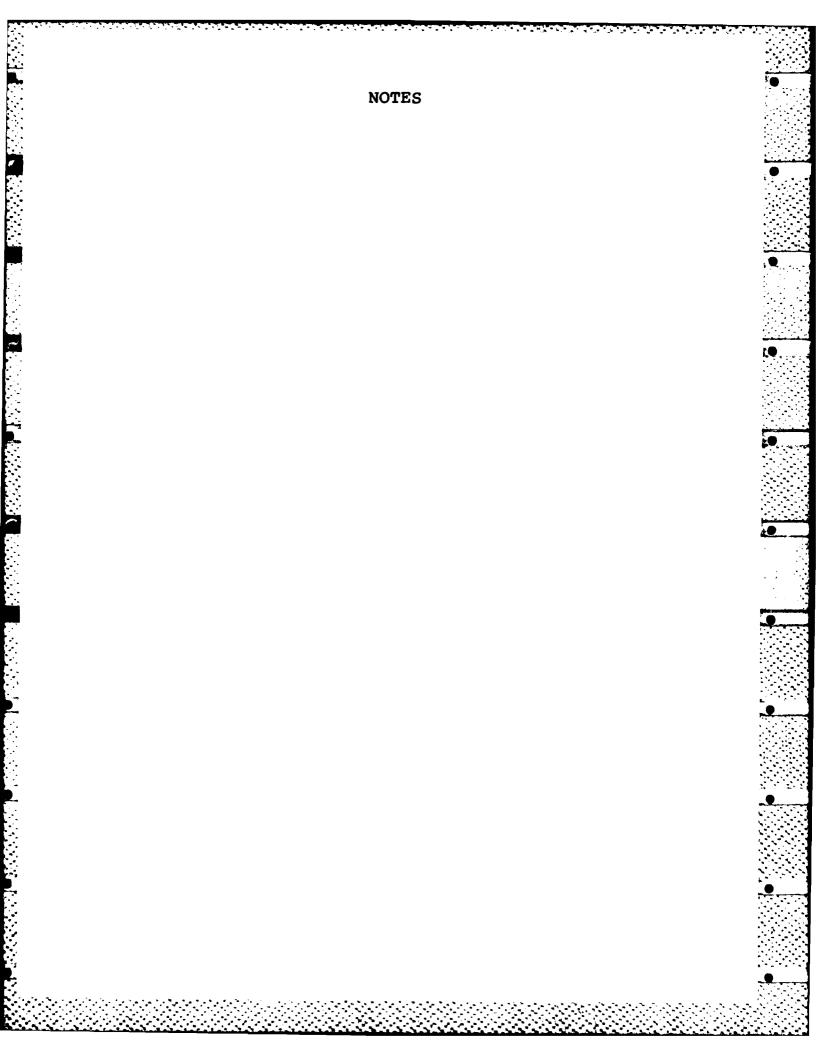
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# GENERATION WITH ELECTRON BEAMS B. Kincaid, *Presider*

Coherent Radiation Characteristics
Of Magnetic Insertion Devices In Modern Storage Rings

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#### Abstract

We discuss the characteristics of radiation from undulators and wigglers in modern electron storage rings. Of particular interest are the coherence properties of undulator radiation which provides an assured route to tuneable coherent radiation throughout the soft x-ray spectral region. We discuss spectral, angular, spatial, and polarization properties of this radiation.

#### Summary

This paper discusses the coherence properties of spontaneous VUV and soft x-ray radiation which will evolve in predictable fashion from the interaction of high brightness, energetic (1-5 GeV) electron beams interacting with many period ( $N \sim 100$ ) permanent magnet insertion devices in modern, low emittance storage rings.

Wigglers and undulators are synchrotron radiation sources through which electrons travel on a sinusoidal trajectory under the influence of an alternating magnetic field. Compact and powerful wigglers and undulators built from permanent magnets generate intense radiation covering a wide range of photon energies. Wiggler radiation, which results from large amplitude trajectory excursions, is similar to bending magnet radiation except for an enhancement of intensity.

Undulators are, however, fundamentally different. In these small amplitude magnetic devices phase information is not lost. With high brightness electron beams the emission spectrum consists of sharp peaks (~ 1/n) at discrete energies, each with angular and spatial distributions concentrated in a narrow radiation cone with surrounding rings. The phase space area of the radiation can be quite small, indicating that the coherent power of undulator radiation can be substantial. The technique for calculating these radiation characteristics will be discussed. In addition to classical techniques for longitudinal and transverse mode selection, we describe a novel scheme for complete polarization control utilizing crossed undulators. Finally, we describe several scientific applications which would benefit from a predictably available, coherent radiation source, tuneable across the soft x-ray spectrum.

Generation of Coherent XUV Radiation Using Lasers and Relativistic Electron Beams

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Coherent soft x-rays can be produced by bunching a relativistic electron beam with a high-powered visible laser.

#### An XUV/VUV Free-Electron Laser Oscillator\*

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A free-electron laser (FEL) oscillator driven by an rf linear accelerator (linac) appears feasible for the extreme- and vacuum-ultraviolet wavelength spectrum from 50 to 200 nm. The design of such a system is projected from the anticipated successful use of rf linacs at high peak currents (~100 A) in forthcoming FEL oscillator experiments at infrared and visible wavelengths by Los Alamos and Boeing/Mathematical Sciences Northwest. An important feature of the linac approach is that electrons pass through the undulator magnet only once, but their energy may be recovered in a separate decelerating structure and fed back into the primary accelerator. Another advantage is the option of unrestricted undulator length. The short pulse duration (10-40 ps) of the laser emission will find application in time-resolved experiments.

As an example, oscillation at 82 nm would involve the following parameters: 1) 200-MeV electrons with 1% total energy spread and 100-A peak current, 2) a uniform-period, 12-m linear undulator with 1.6-cm period and axial magnetic field of 0.75 T, and 3) a 20-m optical cavity with end mirror reflectances of 70 to 80% (projected maximum for present coating technology) and 10 to 20% hole output coupling. A small-signal gain of over 300% has been calculated with a 1-D code for a uniform electron energy distribution which, at saturation, will result in a peak output power of ~300 kW. The corresponding average power will be sufficiently high (up to 200 W) that slightly-curved, grazing-incidence mirrors will be required inside the cavity to diverge the beam and thus reduce the heat loading on the end mirrors.

<sup>&</sup>lt;sup>1</sup>Troy Barbee, Stanford University, personal communication.

<sup>\*</sup>Design study under the auspices of the U.S. Department of Energy and DARPA.

## Extreme Ultraviolet and X-ray Emission and Amplification by Non-relativistic Electron Beams Traversing a Superlattice

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Fast moving electrons emit FM waves when passing through a spatially periodic medium (resonant transition radiation). The wavelength  $\lambda$  of the radiation emitted at an angle  $\theta$  with respect to the electron trajectory is determined by the formula  $\overline{n}(\lambda)\cos\theta=\beta^{-1}-r\lambda/\ell$ , where  $\beta=v/c$  is dimensionless speed at the electron,  $\overline{n}(\lambda)$  is averaged refractive index of the system, r is an integer, and  $\ell$  is the period of spatial modulation. It is conventionally assumed that ultra-relativistic beams are required to attain this kind of emission. We show that if the period  $\ell$  is much shorter than a "mean" plasma wavelength of the medium, (which can be done by using solid-state superlattices with the spatial period 100-200Å), the critical kinetic energy turns out to be extremely low, and one can get a significant radiation in the range 10Å-300Å using non-relativistic beams with energies 70-300 KeV. The spontaneous radiation from the system has a conical structure with the emission wavelength changing with angle. The total radiation power I in each order r per electron is

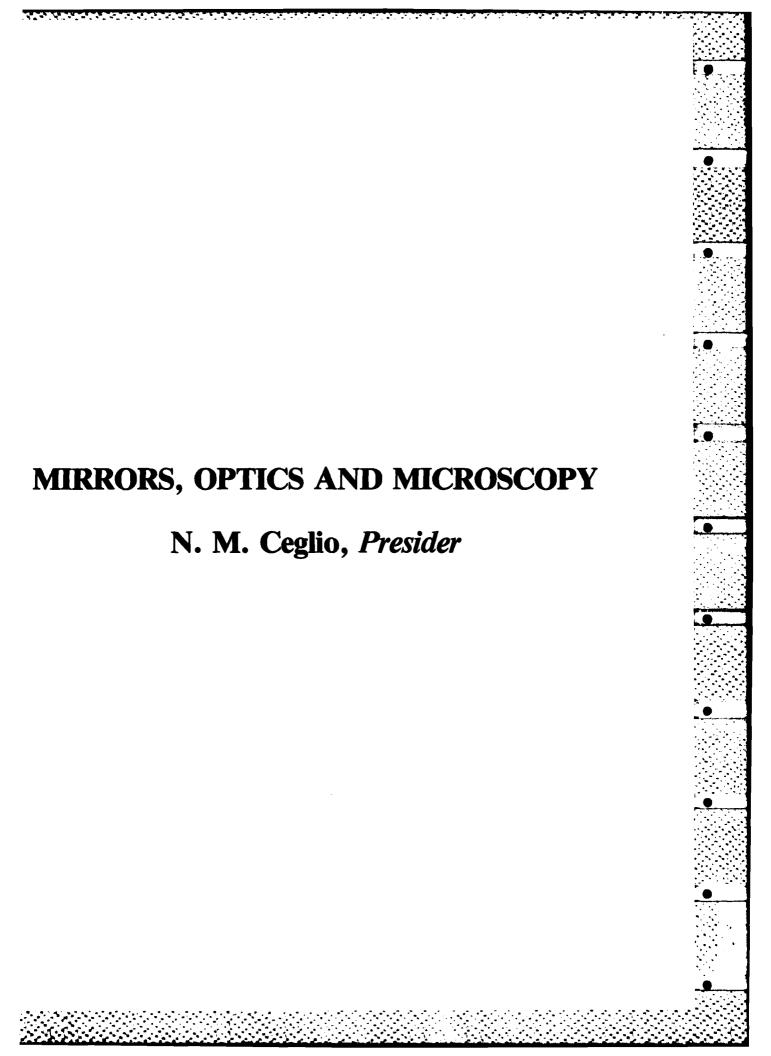
$$I \simeq 16e^{2}L\ell^{2}(\lambda_{1}^{-2} - \lambda_{2}^{-2})\sin^{2}(\pi r\ell_{1}/\ell)/3\beta r^{4}$$
 (1)

the wavelengths of radiation being in the range  $\ell r^{-1}(\beta^{-1}-1) < \lambda < \ell r^{-1}(\beta^{-1}+1)$ . In Eq (1) L is the total thickness of the structure;  $\lambda_1$  and  $\lambda_2$  are the plasma wavelengths of the layers. If  $\ell = 100$ Å,  $\ell_1 = \ell_2 = \ell/2$ , L = 1 $\mu$ m, eU = 75KeV, J = 1mA where J is the total current, and  $\lambda_1 \simeq 400$ Å,  $\lambda_2 \simeq 800$ Å, the system can provide a radiation of first harmonic (r = 1) with a total power  $\sim 0.33$  mW and a mean wavelength  $\sim 200$  Å. If the total current density i is sufficiently large, the system can provide stimulated emission and amplification. The maximal EM wave amplification per pass is

$$\Gamma = 8\lambda^5 \ell^{-1} (\lambda_1^{-2} - \lambda_2^{-2})^2 (\cos\theta + r\lambda/\ell) ieRL^3 \sin^2(\pi r \ell_1/\ell) \sin^2\theta / mc^2\ell \pi^4 \cos\theta, \qquad (2)$$

where  $R = 377 \Omega$  is the vacuum impedance. The required current density i is a high as  $\sim 10^{10}-10^{11} \text{ A/cm}^2$  in order to obtain a considerable gain ( $\sim 5\%$ ), in the range  $\sim 100\text{\AA}$ .

NOTES



#### TuC1-1

llayer Optics for the CUV: Synthesis, Experimental Results, and Projected Performance

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nced vapor deposition techniques have yielded a new class of multi-layer optics soft X-rays. Applications of these processes to fabrication of XUV optics ises significant improvements. Synthesis processes, current experimental lts, and projected performance are discussed.

#### Mirrors for the Extreme Ultraviolet

#### Eberhard Spiller

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High reflectivity normal incidence mirrors do not exist for wavelength  $\lambda$ 1100 Å. There are no absorption-free dielectrics available which can protect a mirror from oxidation or can be incorporated into a loss-free multilayer. Furthermore the reflectivity of all materials decreases with decreasing wavelength to values around 1% at  $\lambda = 200$  Å for the best materials. The reflectivity drops proportional to  $\lambda^4$  at still shorter wavelength with values less than  $10^{-5}$  at  $\lambda = 50$  Å. However, the loss in reflectivity from a single boundary can be compensated by using multilayer structure with many boundaries. Due to the absorption of all materials the coating designs differ from those used for visible light. Peak reflectivities of 20% or more can be obtained at nearly all wavelengths. The theoretically possible peak reflectivity increases with decreasing wavelengths and reaches very high values (R > 80%) around  $\lambda$  = 1 Å. Fabrication of normal incidence multilayer mirrors has concentrated on the wavelength region from  $\lambda = 50 - 250 \text{Å}$  and peak reflectivities around R  $\approx$ 25% have been obtained. The obtained results will be reviewed and the expected performance for other wavelengths will be discussed.

#### VUV Laser Photolithography

by

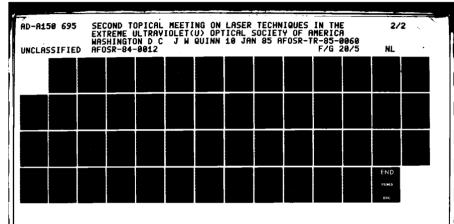
J. C. White, H. G. Craighead, R. E. Howard, L. D. Jackel, and O. R. Wood III

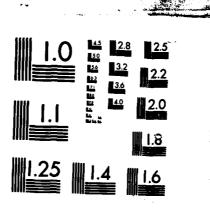
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In this paper we describe experiments using a molecular forine (i.e.,  $F_2$  dimer) laser operating at 157 nm as a vacuum raviolet (VUV) source for high resolution photolithography. F<sub>2</sub> excimer laser is now the only commercially available laser the high average power at a wavelength as short as 157 nm. Ing this laser as a source for contact lithography, we made sist lines as narrow as 150 nm, the smallest features yet produced by photolithography.

Conventional masks with quartz or glass substrates are ague in the VUV, so two alternative mask systems were developed ing substrates that are transparent at 157 nm. The first mask stem used patterned polyimide on CaF<sub>2</sub> substrates and the seconded patterned nichrome on sapphire substrates. Both masks were sterned using electron beam lithography.

The sensitivity and resolution of several resists were idied since little or no data is available on resist properties the VUV. The exposure properties of the resists AZ 2400, R-204, and two compositions of the copolymer of methyl thacrylate (MMA) and methacrylic acid (MAA) were tested. Of





MICROCOPY RESOLUTION TEST CHART NATIONAL BUREAU OF STANDARDS-1963-A

these, the copolymer was the most sensitive. Optical transmission at 157 nm was measured as a function of exposure dose for the resists, since this data is crucial for optimizing the photolithographic processing. In addition, a VUV spectrophotomator has been used to measure optical constants of various resists over the range of 120-200 nm.

The 157 nm exposure source used a Lambda Physik model 101 excimer laser pulsed at 10 Hz with 10 nsec duration and ~0.1 mJ/cm² energy density. Since the laser was highly multimode with little pulse-to-pulse coherence, the problem of laser speckle was eliminated. The contact exposure was performed in a simple vacuum apparatus to avoid strong light absorption from atmospheric oxygen. Features as small as 150 nm were reproduced in the resist. The resist pattern was also used as a mask for reactive ion etching of the silicon substrate, thereby transferring the 150 nm features into a patterned substrate material.

In conclusion, a complete process for vacuum ultraviolet photolithography at 157 nm has been described and was usable in a single layer at 157 nm. Both the PMMA and a copolymer of MMA-MAA were successfully patterned with features as small as 150 nm. The copolymer was used as a mask for reactive ion etching of silicon. Some of the techniques explored may be applied to projection lithography or patterning by photon assisted processes.

#### TuC4-1 Diagnostics for XUV/Soft X-ray Laser

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We have begun investigating the production of an XUV/soft x-ray laser using our high-powered glass lasers as drivers. A major diagnostic for lasing is the measure of the absolute power produced in the lasing line. I have developed a spectrograph to time-resolve lasing lines in the energy range from 50 eV to greater than 200 eV. The spectrograph combines a transmission grating and x-ray streak camera to produce a flat field instrument. A cylindrical mirror is used in front of the grating to image the source and act as a collecting optic. The efficiency of the components are calibrated so that absolute intensities can be measured. I will compare the performance of this instrument with reflection grating systems. I will also discuss planned improvements to the system which should increase total throughput, image quality, and resolving power.

#### NOTES

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## POSTER SESSION UPCONVERSION INTO THE XUV

### Tunable Resonant Enhancement in Nonlinear Optical Frequency Mixing

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The ability to introduce additional resonances in the nonlinear optical susceptibility of a medium by the injection of an additional radiation field is an attractive possibility from the standpoint of efficient tunable frequency mixing processes in the VUV. The possibility of such processes suggest themselves in previous observations in atomic mercury where an enhancement of several orders of magnitude in the third harmonic generation efficiency has been reported when the input frequency is four-photon resonant with the 6S  $\rightarrow$  6D transition (1).

In this paper we employ a two-frequency laser method to study similar mixing processes in mercury involving four-photon resonances with the 6D and 7S levels. By tuning the two input frequencies  $\omega_1$  and  $\omega_2$  so that  $2\omega_1+2\omega_2$  are always in four-photon resonance, the tunable output at  $2\omega_1+\omega_2$  and  $\omega_1+2\omega_2$  should be enhanced by a fifth order process. We establish conclusively that the enhancement in the third harmonic generation efficiency does in fact arise from a resonance in the susceptibility rather than from changes in the index matching conditions due for example to resonant laser ionization processes. Furthermore, we have established that processes up to ninth order in the input laser frequencies can produce contributions to the third harmonic generation process comparable to those of third order processes. About 10% as much third harmonic is generated at the 6D resonance as is produced at the nearby three-photon resonance with 6P. This is for light pulses of a few MW focused by a 25-cm focal length lens in one torr of Hg.

The study of these and similar effects, such as induced resonances in the ionization continuum<sup>(2,3)</sup> may prove to be valuable both in VUV generation and in other nonlinear processes where a tunable resonance is desired. By using a two-input frequency method to study such resonances, we have been able to elucidate the processes contributing to such resonances and and to show that wide tunability can be obtained.

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Generation of VUV Radiation in the Kilowatt Power Range down to 130 nm by Stimulated Raman Scattering in hydrogen

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Raman conversion to shorter wavelengths of visible and UV radiation has been studied by several authors /1,2/. Hydrogen is especially suited because of its large Raman shift and low dispersion.

In plasma diagnostics, there exists considerable interest to determine the concentration and eventually the flux of low-Z-materials such as 0, C, Si, Be, B and others in the plasma-to-wall transition layer by laser-induced fluorescence spectroscopy.

The resonance transitions of these atoms are in the VUV. Methods to generate narrow-bandwidth VUV radiation tuned to the specific wave-lengths are therefore of great interest. It is desirable for maximum signal and ease of interpretation (though not absolutely necessary) to have enough intensity to saturate the transitions.

Inspection of the level diagrams of the elements mentioned reveals that the spectral intervals around 166 nm (C,Be,B,Si), 156 nm (C,Si,B) and 130 nm (O) are of special importance.

In this contribution, we present quantitative power measurements of VUV radiation obtained by anti-Stokes SRS in two different schemes:

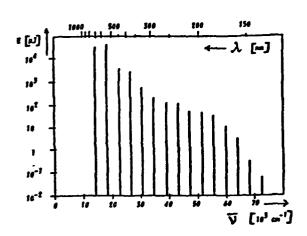
#### First scheme:

We start with a narrow bandwidth ( $\Delta V = .8cm^{-1}$ ) dye laser pumped by a frequency-doubled Nd:Glass laser. The 3-stage longitudinally pumped fluoresceine-27-laser is tunable in the limits 533 nm to 565 nm and yields 160 mJ (15 ns pulse) at 548 nm when pumped with 700 mJ (single shot) of 527 nm-radiation.

For generation of anti-Stokes radiation, the dye laser output is focussed by a suprasil lens into a 1m Raman cell. The  $H_2$ -pressure is varied between 1 and 6 bar. The energy of the visible and near UV AS radiation is measured – after separation by a  $CaF_2$ -prism – by a pyroelectric energy meter. The shortest wavelength analyzed this way is the spectral interval around 193 nm where the power exceeds 10 kW in a 5 ns pulse (this radiation can be further amplified in ArF\* –this was

the reason to choose the specific dye ). The power measurements in the VUV were performed with a monochromator/solar-blind PMT combination; the relative sensitity was calibrated using a  $D_2$ -lamp with

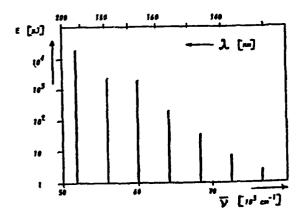
MgF2-window. Relative energies are also obtained this way for the near UV so that a comparison is possible with the pyroelectric detector measurements yielding the absolute scale for the VUV. Fig.1 shows the maximum energies at the optimum pressure for each Raman line. A f=.8 m lens is used as cell window.



#### Second scheme:

Since important pump transitions are located in spectral intervals coinciding with AS-lines starting at 193 nm, we amplified the 8th AS

mentioned above in ArF\* . A
Lumonics TE 262 section and a
Lambda EMG 150 were used
together as amplifiers. 40 mJ
were obtained with a beam
quality sufficient to produce
air breakdown with a 1m lens.
Note that now the shortest
wavelength is 130 nm where
approximately 600 W are
generated in a 4 ns pulse.



The output is tunable over

about 500 cm<sup>-1</sup> /3/. Fig.2 shows the energy of the anti-Stokes lines. On the Stokes side, we observe 7 lines, S1 to S3 exceeding the pump radiation at 193 nm in intensity behind the Raman cell.

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Efficient Generation of Tunable Radiation below 100 am in Krypton

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#### SUMMARY

Tunable, narrowband (< .3 cm<sup>-1</sup>) coherent radiation below 100 nm will be reported. The vacuum ultraviolet photons were generated by making use of the first available two-photon resonance in Krypton [the  $4p^6$   $^1S_0$  -  $5p(2-1/2)_2$  two photon resonance at 216.7 nm] to resonantly enhance the process.

Calculations show that four-wave mixing using two photons at 216.7 nm and one photon near 720 nm would result in negative dispersion near 94 nm in Krypton, which is required in order to produce sum generated output. 1

The vacuum ultraviolet radiation at  $2\omega_1^+\omega_2^-$  was made tunable by fixing  $\lambda_1^-$  at 216.7 nm, while producing  $\omega_2^-$  using a Littman-type dye laser. Since the generated radiation was below the LiF cutoff ( $\sim$  105 nm), differential pumping was necessary. To minimize the loss of Krypton, a novel rotating disk aperture mechanism was utilized. The VUV photons were isolated and detected in three stages: first, the beams were filtered with .5 m McPherson monochromator to isolate the VUV beam. The radiation was then filtered with a 1500 Å thick Indium filter. The fluorescence that resulted from placing a sodium salicylate coated window in the VUV beam path was detected by a Hamamatsu R955 photomultiplier tube.

A conversion efficiency on the order of  $10^{-5}$  was measured, and saturation characteristics of the two-photon resonantly-enhanced process will be reported.

For spectroscopic measurements,  $\lambda_2$  was scanned near 720 nm and the resulting coherent 94 nm radiation was applied to a measurement of weakly autoionizing lines of Xenon. A high-resolution Fizeau wavemeter<sup>2</sup>, which measures wavelengths to an accuracy of better than one part in  $10^6$ , was used to perform a high-resolution scan of the 11s autoionizing resonance in Xenon.

<sup>&</sup>lt;sup>1</sup> G. C. Bjorklund, IEEE J. Quantum Electron., Vol. QE-11, pp. 287-296, June, 1975.

J. J. Snyder, in Laser Spectroscopy, Vol. 3, Proceedings, Third International Conference, J. L. Hall and J. L. Carlsten, Eds. (Springer, New York, 1977), pp. 410-426.; M. B. Morris and T. J. McIlrath, to be published.

#### Continuously Tunable Sum-Frequency Generation Involving Rydberg States

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It has recently been shown that extremely large values of the second-order nonlinear suceptibility can be obtained through use of Rydberg atomic states perturbed by an external electric field. In these experiments a value of  $\chi^{(2)} = 10^{-9}$  esu was obtained using a sodium vapor of number density  $\sim 10^{14}$  atoms cm<sup>-3</sup> and a dc electric field of magnitude 1 kV/cm. One laser was tuned close to the sodium D<sub>2</sub> resonance line while a second laser completed the two-photon resonance with a Rydberg state. A strong coherent UV beam at the sum frequency was generated in the forward direction. The splitting of the highly excited atomic levels induced by the external electric field created a broad region of overlapping levels, leading to continuous tunability. This technique can be applied to any system displaying a Rydberg series. and should be capable of producing coherent, tunable radiation in the extreme ultraviolet.

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Sum Frequency Generation Spectroscopy of Rydberg States

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#### Summary

Consider sum frequency generation (SFG)  $\omega_3$ = 2  $\omega_1$ +  $\omega_2$  in a phase matched metal-noble gas mixture, using two lasers  $\omega_1$  and  $\omega_2$ , where 2  $\omega_1$  is tuned to a two photon transition  $\Omega_{\rm g2}$  and  $\omega_2$  is shifted across Rydberg transitions  $\Omega_{\rm 2n}$  (g groundstate, 2 excited state, n Rydberg state of the metal atom). Then the intensity of the SFG spectrum  ${\rm I}_3$  ( $\omega_3$ )~  $|\chi^{(3)}$  ( $\omega_3$ ) $|^2$  displays resonances and related antiresonances, separated by

$$\triangle c_{n} = \frac{\sqrt{2n^{\prime\prime} ng}}{\sqrt{NR}}; \qquad \Delta \omega_{n} \gg \Gamma_{ng}$$
 (1)

which are caused respectively by constructive and destructive interference of resonant and nonresonant parts of the 3. order nonlinear susceptibility  $\chi^{(3)}$  (  $\omega_3 {\simeq} \Omega_{ng}$ ) =  $\chi^R(\omega_3) + \chi^{NR}$ 

$$\chi^{R}(\omega_{3}) = \frac{\alpha_{2n} \alpha_{ng}}{\Omega_{ng} \omega_{3} - i \Gamma_{ng}} \qquad (2) \qquad \chi^{NR} \sim \sum_{\substack{n' \neq n \\ n' \neq n}} \frac{\alpha_{2n'} \alpha_{n'g}}{\Omega_{n'g} - \Omega_{ng}} \qquad (3)$$

The products  $^{\prime\prime}_{2n}$   $^{\prime\prime}_{ng}$ :=  $\mathbf{x}_n$  of the dipole transition matrix elements may then be obtained from a simple measurement of the frequency spacings  $^{\Delta\omega}_{n}$  at a large number of transitions  $^{\Omega}_{gn}$  and solving iteratively the coupled equation system (1),(3); neither absolute radiation intensity nor vapour density determination is needed. We have applied this method to Cadmium I

numerical computations performed with a one dimensional (z-t) code, CORK, which models the atomic physics and hydrodynamics of the plasma as it ablates from the solid target.

The numerical code includes a fully time dependent collisional-radiative atomic physics package, an option for flux limited heat conduction near the target, and a radial expansion algorithm to account for finite spot size effects. We have found that for 1 GW laser power, the x-ray conversion efficiency is a strong function of spot size, peaking at about  $20\mu$  diameters. The conversion efficiency is only weakly dependent on pulse length for time scales exceeding 100 psec. Better conversion efficiencies are also obtained at shorter wavelengths and for energy matched L and M shell radiators.

We have designed and are constructing a high repetition rate, several hundred milli-joule, 200-300 psec, solid state laser system using a modified commercial oscillator, a slab YAG amplifier, and a tripling crystal. Based on our modeling, this laser will yield 10 percent conversion efficiencies in the 1-2 keV range of soft x-ray energies. We believe that in addition to microlithography, it should find many other interesting applications within the EUV-XUV community.

#### A SOFT X-RAY SOURCE BASED ON A LOW DIVERGENCE, HIGH REPETITION RATE ULTRAVIOLET LASER

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#### SUBCOLKY

The soft x-ray emission of dense plasmas produced by irradiation of solid targets with high intensity lasers has been studied extensively in recent years. Experiments motivated by requirements of the Inertial Confinement Pusion (ICF) program have dominated these studies, but in addition, other experiments have been directed toward the efficient production of soft x-rays for microlithographic and other industrial applications. These experiments have primarily been done using relatively large (E>1 J) lasers operated at low repetition rates.

We have recently concluded a study, funded in part by the National Science Foundation, on the use of sub-joule size, sub-nanosecond, low divergence ultraviolet lasers for the efficient production of soft x-rays for microlithography applications. We find that such small lasers, focused to about  $30\mu$  spot sizes and  $10^{14}$  M/cm<sup>2</sup> intensities, are potentially very useful sources of 1-2 keV radiation. These conclusions are based on

## POSTER SESSION LASER GENERATED X-RAYS

#### NOTES

Optical Pumping of Short Wavelength Fluorescence in Plasmas Using Line
Radiation -- J. Trebes and M. Krishnan, Yale University, New Haven CT 06520.

We have previously reported [1] enhanced fluorescence of the CII, 5d-3p transition at 213.8 nm, when the 5d-2p transition is selectively pumped by AlIII, 56 nm line radiation. The CII ions are produced in a carbon vacuum arc discharge, while the AlIII pump ions are created in an adjacent, laser-produced plasma. Collisional coupling of the pumped, 5d level in CII to the 5f level was verified [2] by observation of enhanced fluorescence at 299.3 nm on the CII, 5f-3d transition. This paper reports simultaneous observation of four different wavelengths in CII, in order to characterize the optical pumping process and the subsequent collisionalradiative kinetics. Measurements are described of electron density (n<sub>e</sub>) and electron temperature ( $T_{\rho}$ ) in the C vacuum arc. The measured values of  $n_{e}$  and  $T_{e}$  are inputs to a time dependent, collisional-radiative model for the CII level populations. Model predictions of the expected fluorescence enhancement, the coupling of the pumped 5d level to other levels in CII, and various loss rates are compared with experiments. The possibility of producing a laser in CII using this scheme is examined. Other candidate pairs for optically pumped, XUV wavelength lasers are presented and discussed.

This research is supported by AFOSR Grant # 81-0077.

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### TuE2-1 Soft X-Ray Spectra, Population Inversions, and Gains in a Recombining Plasma Column\*

H. Milchberg, J. L. Schwob, C. H. Skinner, S. Suckewer, and D. Voorhees

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With the view of developing a suitable medium for soft X-ray lasing action in the strongly recombining phase of a  ${\rm CO}_2$  laser produced plasma, we have concentrated on studying the UV and soft X-ray emissions of hydrogenic carbon (CVI) and the Li-like sequence CIV, OVI, FVII, and NeVIII. These absolutely calibrated spectra, both time integrated and time resolved, have been measured perpendicular and parallel to the plasma column. Plasma density and temperature have been estimated from this data using Stark broadening, recombination continua and dielectronic satellites. Satellites have also been used to estimate self-absorption in lines of interest, especially CVI Lyman  $\alpha$ .

For plasmas with CVI, we have used graphite discs as well as  ${\rm C_2H_2}$  and  ${\rm CO_2}$  pulsed gas targets. Gains have been estimated, with and without time resolution, by comparing CVI (3+2) 182.17% emissions to the spectra measured perpendicular and parallel to the plasma column.

In the Li-like sequence, produced using teflon targets for FVII; gas, macor and graphite targets for CIV and OVI; and gas for NeVIII, population inversions have been measured between the 4d and 3d levels. Gains based on these spectra will be discussed.

<sup>\*</sup>This work is supported by the United States Air Force Office of Research, Contract No. AFOSR-84-0025.

#### Time Evolution, Radial and Axial Distributions of the EUV Line Intensities in CO<sub>2</sub> Laser Produced Plasmas

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A CO<sub>2</sub> laser (1 kJ, 75nS F.W.H.M.) was used to create a plasma from a variety of targets, either solid (e.g. C, Al) or gas (e.g. CO<sub>2</sub>, Ne) in an experiment to develop a soft X-ray laser. An absolute intensity calibrated VUV duochromater was used to observe line emission from the plasma. A scanning slit assembly limited the field of view of the duochromator to a region 1 mm x 0.1 mm, the long dimension being normal to the target. By scanning the slit and target position the radial and axial distributions of the line intensities were built up on a shot-to-shot basis for the different targets.

We will present data showing the effects of external magnetic fields, and different laser powers on the plasma. We will discuss changes in the line intensities when additional elements (e.g. Al, Xe) were added to the plasma and, for the case of gas targets, the effect of varying the gas density.

The absolute value of the excited state populations, the plasma dimensions, the degree of spatial homogeneity and the effectiveness of radiation cooling will be assessed in terms of that necessary for a soft X-ray laser.

<sup>\*</sup>This work is supported by the United States Air Force Office of Research, Contract No. AFOSR-84-0025.

# POSTER SESSION XUV LASERS

Measured Radiative Lifetime of Rovibronic Levels in  $A'\pi(v=0)$  State of CO, and Comparison with Theory

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VUV radiation was generated by
mixing N<sub>2</sub>-pumped dye-laser beams (2 ns)
in Mg vapor, and LIF used to measure
lifetimes of perturbed levels from J' = 0 to 29.

- a Poster Paper.

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pump energy. Our initial measurements with phase matched mixtures of Xe and Ar indicate that the conversion efficiency increases by a factor of about 2 when a 5:1 Xe:Ar mixture is used. Further improvements in phase matching, the use of various gas combinations and their effects on breakdown and absorption limitations will be discussed. Scaling of our current results indicate that the conversion efficiency can be raised from 2 x 10<sup>-4</sup> to 10<sup>-3</sup> with a corresponding increase in VUV energy to 1 mJ if the pump energy is raised to 250 mJ and the nonlinear medium can be confined to the region of the nonlinear interaction. The usefulness of various gas confinement techniques for the conditions required by our high pump laser power (large apertures, long interaction paths) will be described and the results of conversion efficiency measurements at high pump energy will be reported.

High Energy VUV Pulse Generation by Frequency Conversion

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The efficiency with which VUV radiation can be generated by frequency conversion has been limited by various competing processes to values that are typically of the order of 0.1 - 0.3%. As a result, increases in available VUV pulse energy will have to be made through increases in the pump laser energy. However, the use of higher pump laser power can be accompanied by additional limitations associated with various experimental parameters, especially in the VUV where tight focusing and short interaction lengths are usually used. For example the larger focal spots that must be used with stronger pump lasers to avoid breakdown are necessarily accompanied by longer interaction paths that can make absorption in the nonlinear medium and damage to cell windows more important. We have conducted a series of experiments in third harmonic conversion of XeF laser radiation in Xe to determine the extent to which the additional problems associated with high pump power can be overcome. Our initial experiments, done at a pump energy of 20 to 30 mJ (2 MW peak power) have indicated that the conversion efficiency, which was measured to be of the order of  $5 \times 10^{-4}$ , was limited by a combination of breakdown in the focus and absorption of the VUV radiation in the Xe downstream from the nonlinear interaction. The corresponding pulse energy was measured to be of the order of 10 µJ without phase matching. Further increases in VUV pulse energy can be accomplished with a combination of phase matching and increased

This research was sponsored by the Office of Health and Environmental Research, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

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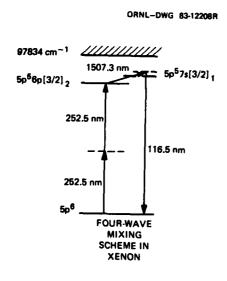


Figure 1

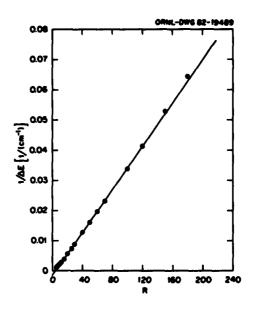


Figure 2. Phase-matching curve

Direct Measurement of a Vacuum Ultraviolet Transition
Oscillator Strength in Xenon

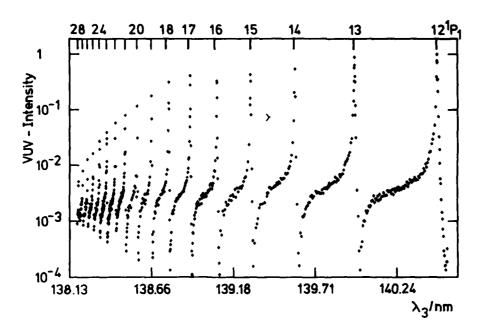
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The oscillator strength, f, of the xenon 7s[3/2]<sub>1</sub> state was directly measured by determining the phase matching condition for four-wave sum mixing in xenon-argon gas mixtures. The vacuum ultraviolet (VUV) mixing scheme for xenon is shown in Fig. 1.<sup>1</sup> Optical mixing with a pair of pulsed dye lasers was used to produce the six-nsec long input beams at 252 and 1507 mm. The generated VUV output near 116.5 mm was tuned by varying the 15° input. The VUV pulse energies of up to 1 µJ were measured using a separate nitric oxide ionization chamber.

In this VUV region the phase-matching condition is determined primarily by the proximity of the 7s state. With partial pressures of xenon above 10 Torr, the phase-matching condition is independent of the detailed mode properties of the input beams and can be written<sup>2,3</sup> as  $1/\Delta E = a + (b/f)R$ , where  $\Delta E$  is the energy difference between the generated VUV light and the 7s state, a and b are essentially constants where b was calculated from the known refractive index of argon,<sup>4</sup> and R is the ratio of the argon to xenon partial pressures needed to optimize the VUV output for a given  $\Delta E$ .

The points in Fig. 2 show the experimentally determined values of  $1/\Delta E$  versus R. They have the linear relationship predicted by the equation and give  $f = 0.12 \pm .03$ . This is consistent with previous values obtained from considerably more complicated electron loss measurements.

and measured  $I_3(\omega_3)$  in the range of the principal series  $5s^1s_0 \rightarrow np^1p_1$ , n=12-28 (see figure). For evaluation of the corresponding  $x_n$  we included theoretical values for n=5-11 1)2) contributing to  $\chi^{NR}$ . The  $x_n$  turn out to obey the  $n^{*-3}$  law for n=12-28. The matching to the  $x_n$  for n<12 is achieved only by using the correct sign of  $x_5$ , which is predicted to be negative from theory  $^2$ ). Additional measurement of  $|\mu_{ng}|^2$  using the modification of  $I_3(\omega_3)$  due to mismatch yields the individual  $\mu_{2n}$ . This, together with the information on its sign relative to  $\mu_{ng}$  opens the possibility to test recent pseudo-potential approaches in the theory of heavy atoms with several valence electrons  $^{3)4}$ .



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#### X-Rays Generated by Laser Irradiated High-Z Targets

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The X-ray emission from laser irradiated high-Z targets has received much attention in the recent years. The two main centers of interest were: spectral studies for the determination of plasma parameters and conversion efficiencies for understanding the plasma energetics. We have performed these kinds of experiments at Limeil during the three past years using spherical and planar targets (Glass, Aluminum, Gold, Copper) and modifying irradiation conditions (laser wavelength and flux).

In this paper, we present a description of the diagnostics and the methods used to unfold the experimental results. To analyse these data we have three threoretical tools:

- The Limeil one-dimensional FCI 1 code.
- Corine: a model for emission and transfer of the radiation in laser plasma, using stationary temperature and density profiles and an atomic physics coupling local thermodynamical and coronal equilibria.
- Analytical expressions to explain qualitatively the experimental results about X-ray conversion efficiencies.

The set of experimental and theoretical results are coherent with other laboratories' ones and shows the growth of X-ray efficiency when target Z and pulse duration increase and when the laser wavelength  $\lambda$  decreases. The maximum of the efficiency appears for a laser flux  $\phi$  about  $\phi\lambda^2 \sim 5. \times 10^{13}$  W/cm<sup>2</sup>  $\mu$ m<sup>2</sup>.

# NOTES

# LASER GENERATED X-RAYS David Nagel, Presider

#### Dynamical Aspects of the Picosecond X-ray Generation from Laser-Produced Plasmas

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#### **Abstract**

Systematic studies of the generation of picosecond x-ray pulses from laser-produced plasmas are performed experimentally and theoretically. The present understanding of dynamical aspects of transient x-ray generations are reviewed.

Studies of the x-ray pulse generation from picosecond laser-produced plasmas are very important not only from the standing point of the physics itself but also for the purpose of the development of x-ray laser and x-ray induced implosions. However, both dynamical mechanism of the picosecond x-ray generation and various related transient characteristics have not yet been clarified. Usually theoretical analyses are mainly concerned with plasmas in the steady-state equilibrium results which clearly show transient and experimental characteristics of x-ray generations are quite few. We have carried out systematic studies of the picosecond x-ray generation both experimentally and theoretically with careful attentions for dynamical atomic processes such as three body recombinations, radiative recombinations, electron captures and innershell excitations, in addition to hydrodynamic motions of recombining plasmas. By these studies, many transient characteristics associated with x-ray radiations in both continuum and line spectra are revieled for the first time. In the present paper, the present status of our studies and the present understanding of dynamical aspects of the picosecond x-ray generations are reviewed.

As to continuum x-ray radiations, various target materials are used in order to investigate the dependence of the intensity of emitted continuum x-rays on the atomic number of target materials by using 30 ps,10 GW  $Nd^{+3}YAG$  laser. In our analysis, we adopt the transient collisional radiative model, in

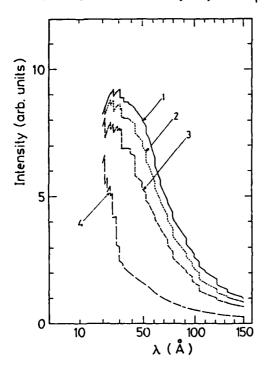
which equations employed in the model are expressed as follows;

 $dn_j/dt = n_e(n_j \bowtie_j - n_j(S_j + \bowtie_{j-1}) + n_{j-1}S_{j-1}); 0 \le j \le Z$ . Here,  $n_j$  is population density of ion species with the atomic number Z in charge state  $j, S_j$  is collisional excitation rate (cm  $^3/\text{sec}$ ),  $\bowtie_j$  is recombination rate (cm $^6/\text{sec}$ ). By solving these transient coupled rate equations, periodic features observed in the emitted x-ray intensities which are strongly dependent on atomic numbers(Z) are well understood. The dependence of transient analysis based on the transient collisional radiative model was also clearly shown $^2$ .

to transient line emissions from highly ionized ions,x-ray intensities are calculated as functions of time in picosecond regions by computationally temporal variations of densities of each excited level of each charged state. Intensities of x-ray line emissions from plasmas in recombining phase were computed. In the framework of the model which discribes dynamical characteristics of recombining plasmas by solving coupled equations representing hydrodynamic motion of and radiation processes of highly ionized Usually, electron temperature and densities are estimated for transient, recombining plasmas by comparison of their line spectra with theoretical calculation assuming for plasmas in steady states. We discuss inaccuracy of this method and how severely electron temperature and densities thus obtained are suffered from uncertainty due to the transient change of 0n emission spectra. the basis of our results, right understanding is given for analysing experimental results performed by M.H.Key et al.<sup>3</sup>. As to origins of satellite line emissions, important role of atomic processes

collisional innershell excitations and radiative transitions from the next higher charged states will be briefly discussed.

A typical result of computer simulations of time-integrated x-ray continuum spectra are shown in Fig. to show how strongly spectra are modified depending on the time of measuring. Spectra indicated by 1,2,3 and 4 represent simulated at 10,20,30 ps and steady state condition,



respectively. These transient characteristics of x-ray lines related transient processes will be clarified to some extents by measuring time resolved spectra with the aid of newly developed streak cameras. To perform picosecond a spectroscopy in XUV region is first step desirable as a possible population observe inversions in these wavelength

Fig. Computationally obtained regions. We developed a flattime integrated x-ray spectra field grazing incidence XUV spectrograph(15 300 A)equipped

with varied groove pitches  $^4$ . By this spectrograph newly developed, we have already stated measurements of picosecond time resolved spectra in XUV regions. We are also developing 4 beam, ultra-short picosecond TW class glass laser systems equipped with 20 cm clear apperture disk amplifiers for carring out basic studies of x-ray lasers  $^5$ . Further studies of x-ray lasers will be performed by using this new laser systems.

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Experimental and Simulation Studies on Soft-X-Ray Emission from 0.53  $\mu m$ -Laser Irradiated Solid Targets

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The spectrum-resolved radiant energy in  $0.17 \sim 1.6$  keV range from various plane targets irradiated by a  $0.53 \mu m$  laser at  $0.15 \sim 1.0$  nsec pulse through a f/1.4 lens with a nominal incidence angle of either 54° or 0° were obtained by a mutually complementary use of a transmission grating spectrometer, multi-channel filtered X-ray diodes and X-ray calorimeters. Atomic number dependences of the spectrum and X-ray conversion efficiency are described. Especially the radiation investigated at the Au target is concluded to be significantly deviated from the blackbody radiation at the laser intensity range  $2 \times 10^{13} \sim 2 \times 10^{15}$  W/cm<sup>2</sup>. The conversion efficiency increases as laser pulse duration. The increase at normal incidence is infered to be mainly due to the increase in the laser absorption.

These X-ray emission spectra are investigated by the

1-D hydrodynamic Lagrangian code HIMICO and 2-D particle-in-cell code IZANAMI, both of which are coupled with non local thermodynamic equilibrium (non-LTE) average ion model and multi-group radiation transport. The emitted spectrum by LTE model has significant amount of high energy component compared with that by non-LTE model, and disagrees with the experimental result. The physical meaning of the experimentally obtained spectrum is clarified and the total emitted power density proves to have maximum at certain combination of density and temperature. The 2-D code simulation shows that the laterally directed radiation from an expanding plasma, especially at a longer laser pulse, illuminates the edge parts of the laser spot and heats them. Such lateral radiative energy transport becomes significant at least in high Z targets.

The spectrum and temporal behavior of the emission from a laser-heated large volume plasma confined by walls will be discussed.

Finally, the application of these emissions to ICF and X-ray lithography will be reviewed.

#### MEASUREMENTS OF PHOTOIONIZATION CROSS SECTIONS OF IONS IN THE EXTREME ULTRAVIOLET

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Absorption spectra of He-like and Li-like ions of light elements (Be, B, C) have been recorded using two laser produced plasmas 1; one acts as a background continuum emitting source and the other as the target for the absorption experiment.

Measurements have been performed on both the grazing incidence (20-300 A) and the normal incidence (300-1500 A) regions.

The recording is made with a combination of scintillator and intensified photodiode array detector coupled with an optical multichannel analyzer.

Fig. 1 is a sketch of the experiment.

The method allows the measurements of photoionization cross sections and of possible resonances in the cross section. The absolute value of the cross section is established by evaluating the line density with the known oscillator strengths of the series of resonance lines through a model that takes into account the shape of the lines and the instrumental function.

We have measured the Be III cross section from threshold up to 400 eV and found it in very good agreement with theoretical predictions.

The profile of the autoionized 1s<sup>2</sup>-2s2p line of Be III has been measured and fitted to Fano parameters. Similar results for other ions will be reported.

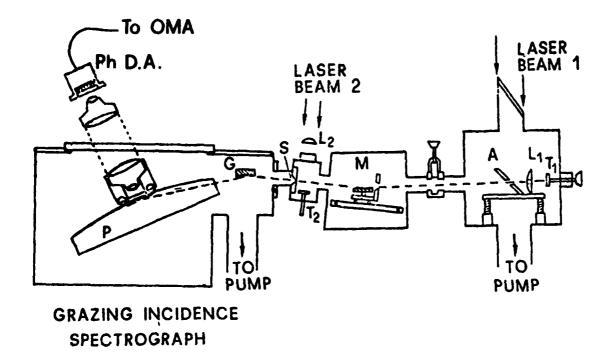


Fig. 1

1 - E. Jannitti, P.Nicolosi and G. Tondello to be published Physica C.

# XUV LASERS Martin Richardson, *Presider*

#### AMPLIFICATION OF SPONTANEOUS EMISSION IN ALUMINIUM AND MAGNESIUM PLASMAS

#### P. JAEGLE

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#### SUMMARY

Experiments performed in recombinating aluminium plasmas have shown, for various conditions of plasma production, that population inversions occur between the levels 3, 4, 5 of lithium-like ions (1-4). In references 1 and 4, inversions between 3d and 4d or 5d levels have been deduced from the analysis of line intensity ratios corresponding to 2p-nd transitions. In references 2 and 3, the evidence of an inversion between the 3d and 5f levels resulted directly from the behaviour of the 3d-5f line for relevant changes in plasma geometry in the line of sight. Numerical modelling, in which rate equations are solved for 22 levels, has suggested that the explanation of these inversions refers to the recombination scheme (5).

Here we describe the experimental method, which we have brought about in order to measure the amplification of spontaneous emission (A.S.E.) going with population inversions in hot plasmas. This method intends to make use of the only criterion which remains valid in small volumes of material, like laser-produced plasmas are. At the density

of interest (10<sup>19</sup>- 10<sup>20</sup> cm<sup>-3</sup>) a plasma column of a few millimeter length is optically thick for most of the X-U.V lines and it may have a non-zero absorption coefficient in the continuous spectrum itself. Thus, if the absorption spectrum of the plasma is worked out—what we do from accurate measurements of intensity dependence on plasma length— the occurence of a peak of negative absorption does give the evidence of A.S.E. at the corresponding wavelength. We observe actually such peaks at 105.7 Å and 103.8 Å in aluminium, at 127.8 Å and 125.5 Å in magnesium with a magnitude about 1 cm<sup>-1</sup>. This value depends on energy, length and shape of the laser pulse which produces the plasma. The continuous spectrum absorption coefficient is a function of the same experimental parameters and it may reach values large enough to cancel the effective gain. Optimal plasma conditions have to be found for a suitable balance of these opposed effects.

Regarding the excited levels of Li-like ions, the stationary solution of the rate equations reveals large discrepancies among the levels as for the effect of plasma electronic density on their populations. As a result, the 3d-5f calculated inversion exhiluts a maximum at  $10^{18} - 10^{19}$  cm<sup>-3</sup> in a temperature range of 100-300 eV. All the inversions disappear at about  $5.10^{20}$  cm<sup>-3</sup>. The time dependent solutions provide more details on the electron density effect in showing the population speeds of some levels to be inverted when the density increases from  $10^{17}$  cm<sup>-3</sup> to  $10^{19}$  cm<sup>-3</sup>. Rather than an exact prediction of physical processes, these calculations are an useful tool for choosing the best experimental plasma conditions.

In the next future, the effort will bear on target design, laser pulse shaping, plasma length; in addition a first attempt will be made for using multilayer mirrors in the amplification diagnostic (6).

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#### Population Inversion and Gain in Expanding Carbon Fibre Plasmas

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#### Abstract

Carbon fibres of a few microns diameter, heated by a Nd:glass laser pulse offer a suit ole medium for the generation of gain in the XUV spectral region. Population inversion occurs as recombination is induced by adiabatic cooling in the expansion of the hot fibre. Experimental results and their interpretation using computer modelling have given a good understanding of the underlying physics, and show two regimes of operation: one of high gain places stringent limitations of the uniformity of illumination, the other of lower gain of the length of cylindrical focus.

Nd:glass laser radiation, and its harmonic as a working medium for laser action in the XUV has been investigated both experimentally and theoretically. In this system rapid cooling by adiabatic expansion of the fully stripped carbon plasma induces population inversion between the n = 3 and n = 2 levels of the hydrogenic like carbon ion C VI during the recombination cascade. In general the gain in such a system is small, limited by the optical trapping of the lower laser level n = 2. However, if the scheme is to have an application with current technology amplified spontaneous emission or travelling wave mode of operation is necessary, requiring a relatively high gain. This condition can only be achieved if the resonance line can be made optically thin at a reasonably high density.

In the carbon fibre system this handicap is mitigated by two effects. Firstly the carbon is initially fully stripped, and only relatively weakly ( $^{\circ}$  10%) recombined at gain onset to reduce the Lyman  $\alpha$  ground state population. Secondly the effective plasma width is kept small. This latter condition is achieved both directly by using fibres of small intial diameter, but more importantly due to the approximately linear dependence of the radial velocity, and the motional Doppler effect, which ensures that only a limited width of the plasma is in resonance at line centre.

It is clear from the above remarks that there is only a restricted region of parameter space in which high gain can be achieved. If the plasma is too cold severe recombination to the ground state gives rise to strong reabsorption of the Lyman  $\alpha$  line; on the other hand if too hot recombination population of the upper states is weak. Thus we would expect that for constant plasma dimensions there is an optimum imput energy for peak gain. Furthermore since the opacity limitation is

weakened, both directly and due to larger velocity gradients, by smaller transverse dimensions, the gain may be increased by using smaller initial fibre mass per unit length. This behaviour has been confirmed by computer modelling of uniformly heated plasma cylinders.

In an experiment the diameter of fibre used is limited by practical considerations such as visibility of alignment, stiffness, to not less than Such fibres may be relatively thick to heat uniformly, and about 3 um. only a limited mass of carbon may be heated (hot plasma) leaving behind a residual core of cold dense material. Since the residual core is cold it remains at approximately the initial fibre radius, and plays no role in the hot plasma expansion. In this way a plasma of smaller effective mass than the fibre mass may be generated: however, in this case the plasma mass and energy are not independent, but the former is determined by the latter in some way depending on the time history of the heating. case also angular symmetry cannot be a priori assured, but must be obtained by the structure of the hot plasmas itself2. calculations allow the construction of a plasma mass/energy plot for given laser pulse characteristics (fig. 1). We may superimpose on this the mass/energy plot for uniformly heated plasmas giving optimal gain to identify those regions in which gain can be expected. In general there appear to be two such zones - one at low energy, low mass and one at high, the latter corresponding to complete burn. Experimental measurements of effective mass are in reasonable agreement with calculated values.

The highest gains will clearly occur in the low energy region, and have been experimentally observed<sup>2</sup>. However, the window of operation is extremely narrow, as an increase in energy rapidly leads to a region of absorption. This will place stringent limitations on the design of a practical working laser, and recent work<sup>3</sup> has therefore been directed at

lower gain, larger energy and mass systems. In these it is essential that the fibre be fully burnt through if gain is to be detected in a time integrated experiment unless the fibre is about lcm long. A recent experiment, in which this condition was not achieved due to low laser energy coupling (6%), provided data confirming the computational modelling of the mass/energy relationship, and verified the necessary parameters for operation in this regime.

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#### SUMMARY

X-Ray Laser Spectroscopy

Ъу

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Emissions from certain resonance lines which are considered to be promising source candidates for matched-line photoexcitation pumping of plasma x-ray lasers have been measured and are found to be near the saturation level. This is supportive of current numerical modeling and laser experiments. The radiation is emitted from high density plasmas near the surface of laser-heated slab targets of selected materials. Among numerous possible ion combinations to be surveyed, a very promising test case involves Na<sup>9+</sup> ions pumping Ne<sup>8+</sup> ions for lasing at 23, 7.8 or 5.8 nm wavelengths. Spectra from frozen neon targets which include the Ne<sup>6+</sup>-Ne<sup>8+</sup> ions will be presented.

#### NOTES

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